AGGREGATE AND COLLOIDAL STABILITY CHARACTERISTICS IN IRRIGABLE TROPICAL SOILS

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INTRODUCTION

Stable soil structure is desirable in agricultural soils because good aggregation is correlated with favorable physical conditions for crop growth. Good drainage, sufficient aeration, easy handling during ploughing, as well as other reasons, are all consequences of favorable soil structure. High correlations also exist between the stability of soil aggregates and other soil physical properties, particularly those related to erodibility and water infiltration and movement characteristics. Thus an assessment of stability classes for different soil types or aggregates would be a useful tool for predicting the physical properties of soils.

Salt affected soils are among the problem soils that are faced in agriculture. These may be saline, sodic, or saline-sodic soils that are commonly encountered in irrigated areas of arid and semi-arid regions. Saline soils are soils with excessive concentration of soluble salts while sodic soils are those with excessive amounts of exchangeable sodium. Harmful effects on plants are noted with all types of salt-affected soils. Unfavorable soil physical conditions, such as poor permeability, are more characteristic of sodic soils due to unstable soil structure. This is particularly true for those that are not saline.

In temperate zones, where soils with mainly 2:1 clays as their major mineralogical constituents prevail, an exchangeable sodium percentage (ESP) of 15% or more has been known to cause deterioration of soil structure. Among the factors that influence aggregate stability, in addition to types and relative amounts of exchangeable cations and

concentration and composition of electrolytes in soil solutions, are the proportions of organic matter, oxides and hydroxides of iron and aluminum, calcium carbonates, clay sized particles, and relative abundance of different soil minerals. Studies on the effect of remoulding of homoionic soils under different moisture contents on their dispersion behavior is desirable in order to predict the stability of agriculture soils undergoing mechanical cultivation.

It has been found by many workers that there is a close relationship between hydraulic conductivity of the soil and the flocculation behavior of the colloids, and that decreases in soil permeability are due to breakdown and subsequent deflocculation or dispersion of constituents of soil aggregates.

It is also well established that under certain conditions, the charge balances on clays can determine their tendencies to flocculate or to disperse. The higher the net charge, the greater the dispersion. For a given charge, the dispersion increases with increasing ionic hydration, decreasing electrolyte concentration, and smaller valencies of the adsorbed or exchangeable ions. Flocculation of clays is generally easily accomplished by the addition of small amounts of neutral salts. The flocculation powers of electrolytes for a given sol or suspension vary considerably for different types of electrolytes. The measure of relative effectiveness of different electrolytes in flocculating the suspension is obtained from "Flocculation Series Tests." In such tests, the "Flocculation Value" is obtained, which is the amount of electrolyte required to reduce the stability of a sol to a certain level--a useful relative measure of the original stability of the sol (van Olphen, 1963).

The amount of electrolyte required to produce flocculation decreases as the valency of the added cations increases, or as stated in terms of the Schulze-Hardy rule, "The flocculation value is primarily determined by the valence--rather than type of those ions with a charge opposite to that of the particle." However, the minimum concentration of an electrolyte required, varies with the pH, the nature of the adsorbed cations and the concentration of the suspension or sol.

Thus in the field, if the concentration of the soluble salt (electrolyte) in a soil (particularly one undergoing mechanical disturbance) is higher than this flocculation value, it may be predicted that the soil will remain flocculated, and favorable conditions for the formation of secondary aggregates should prevail.

The objectives of this study were:

1. To determine stability classes for natural aggregates of selected Hawaiian soils.
2. To establish the colloidal stability characteristics of the fine fractions of these soils.

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LITERATURE REVIEW

Charge Characteristics of Clay Minerals and Other Components in the Soil

The cation exchange capacity (CEC) of kaolinite-type clays is between 1 and 10 me/100 gm but the source of the negative charge on these minerals is debatable. Some workers believe that the negative charge is due to isomorphous substitution, while others suggested that it arises from broken bonds at the edges of the tetrahedral and octahedral sheets exposing the hydroxyl groups. Ionization of hydrogen ions results in negative charge and protonation in a positive charge. Van Olphen (1963) (after Thiessen, 1942) showed that negative gold particles adhered to the edges of kaolinite minerals which suggested that these edges were positively charged. Many other workers (as cited by Grim, 1953; Schofield and Samson, 1954) showed that there is a positive adsorption of anions by kaolinites. Schofield and Samson (1954) also showed that a change of positive adsorption to negative adsorption of chloride occurred when NaOH was added. The source of these positive charges are speculative. It was believed by Wiklander (1964) and Schofield and Samson (1953) that they are pH dependent, becoming negative at higher pH and positive at lower pH. Amorphous constituents were also observed to have been adsorbed on kaolinite surfaces (Follet, 1965) and other clay mineral surfaces (Jones, et al., 1973).

The CEC of 2:1 clays is between 80-100 me/100 gm. While the crystalline kaolinite-type clay particles are relatively large and thus have low specific surface area, the 2:1 clay minerals are small and therefore have larger specific surface areas. The latter are also

presumed to exhibit little or no charge dependence on the composition of the solution environment.

In highly weathered soils, silica is leached, leaving soils that are enriched in oxides and hydroxides of iron and aluminum, as well as amorphous constituents. All these constituents are reactive in nature, possessing surface charges of their own. It is known that the sign of these charges are dependent on the pH and composition of the surrounding medium, behaving as anion exchangers at low pH values and as cation exchangers at high pH values.

Present in the soil colloids are also colloidal organic compounds which may behave as negatively charged, polar, or amphoteric in nature. Negative charges may originate from COOH and OH groups of many organic compounds, such as humic acid, aminoacids, proteins, and other compounds. Other compounds which are polar and amphoteric in nature may behave as proton acceptors in acidic media and as proton donors in alkaline media. As proton acceptor the polar molecule will become positively charged, capable of anion exchange and when as proton donor, it becomes negatively charged capable of cation exchange.

Parks (1967) listed the zero points of charge (ZPC) and isoelectric point (IEP) of some clay minerals. According to his list, montmorillonite has a ZPC of $\leq$ 2.5 while kaolinite has a ZPC ranging from 3.3 to 4.9. According to Parks (1965), the range of IEP was 5.2 - 8.6 for Fe_2O_3, 12 $\pm$ 0.5 for $Fe(OH)_2$, approximately 8.5 for $Fe(OH)_3$, 5.0 - 9.2 for Al_2O_3 and 5.0 - 9.25 for $Al(OH)_3$. The clays, oxides and hydroxides are positively charged below these values and are negatively charged above. Since montmorillonite has a very low value, it does not develop positive

charge under natural soil pH conditions. Generally kaolinite would carry a negative charge under natural conditions while the oxides and other amorphous constituents are positively charged. Thus layer silicates and metal oxides may be mutually flocculated in soils.

Application of the Theory of the Stability of Lyophobic Sols to Aggregate and Colloidal Stability Studies of Soils

It was first demonstrated by W. B. Hardy in 1900 that there is a relationship between the effects of electric fields on colloidal systems and their stabilities by showing that the coagulation of denatured albumin by salts paralleled the reduction in electrophoretic velocity of the particles. Other physical properties known to be affected by interparticle forces are viscosity, swelling, shear strength, and other properties. Many investigators later put into perspective interconnections between these physical variations and ionic exchange phenomena in soil science (Marshall, 1964).

The negatively charged clay particles have positively charged ions (cations) adsorbed and accumulated near their surfaces and around their edges. In the presence of water, or in the case when the clay particles are dispersed and suspended in electrolyte solutions, the distribution of cations near the clay surfaces occurs in such a way that there is a higher concentration of cations near the clay particle surface due to electrostatic attraction and this concentration tends to decrease with increasing distance from the particle surface due to diffusion forces. The similarly charged clay particles are also subjected to mutual repulsive forces between themselves and with other ions of the same

charge. Thus the anions are excluded away from the negatively charged clays. This is called "negative adsorption" or the Donnan exclusion phenomenon. This layer of negative charges carried by clay particles with that of compensating cations and repelling anions is known as the "electric double-layer."

Several models of this electric double layer have been suggested by many investigators. Helmholtz (1879) was the first to discuss this double layer phenomenon quantitatively using the model of a solid condenser immersed in solution. Later, other workers, for example Gouy (1910, 1917), Chapman (1910), Stern (1924), and Verwey and Overbeek (1948) developed the theory for more practical situations in colloidal systems.

From electrostatic and diffusion theory, the Boltzmann equation which computes the exact distribution of positive and negative ions as a function of distance was developed. In general, the Boltzmann equation has the form:

$$n_i = n_i^o \exp - \frac{Z_i e \psi}{KT}$$

where n_i = concentration of ion at a certain point expressed as ions per cm^3

n_i^o = concentration of the ion in the outside solution as ions per cm^3

Z_i = valency of the ion

ψ = potential at that point

e = electronic charge

K = Boltzmann constant

T = absolute temperature

Figure 1 shows diagramatic representation of the distribution of cations and anions as a function of distance from a surface of negative charge, as computed by the Boltzmann equation. The level BD indicates the concentration of both cations and anions at a large distance from the surface. The average local concentration of cations is given by DA, and that of the negative ions by curve DC. The total excess of counter ions is represented by surface area BAD, the total deficiency of ions of the same sign by surface area BCD. The surface area CAD therefore represents the total net diffuse layer charge, which is equivalent to surface charge.

The average electric potential at any point with respect to a point far removed from the surface can also be computed. The Boltzmann equation describes the ion distribution and the Poisson equation describes the potential distribution, and their combination results in what is called the Poisson-Boltzmann equation:

$$\frac{d^2\psi}{dx^2} = \frac{8\pi nZe}{\epsilon} \operatorname{Sinh} \frac{Ze\psi}{KT}$$

in which, $\frac{d^2\psi}{dx^2}$ = variation in field strength w.r.t. distance

n = concentration of electrolyte

Z = valency of the ion

e = electron charge

ϵ = dielectric constant of the medium

K = Boltzmann constant

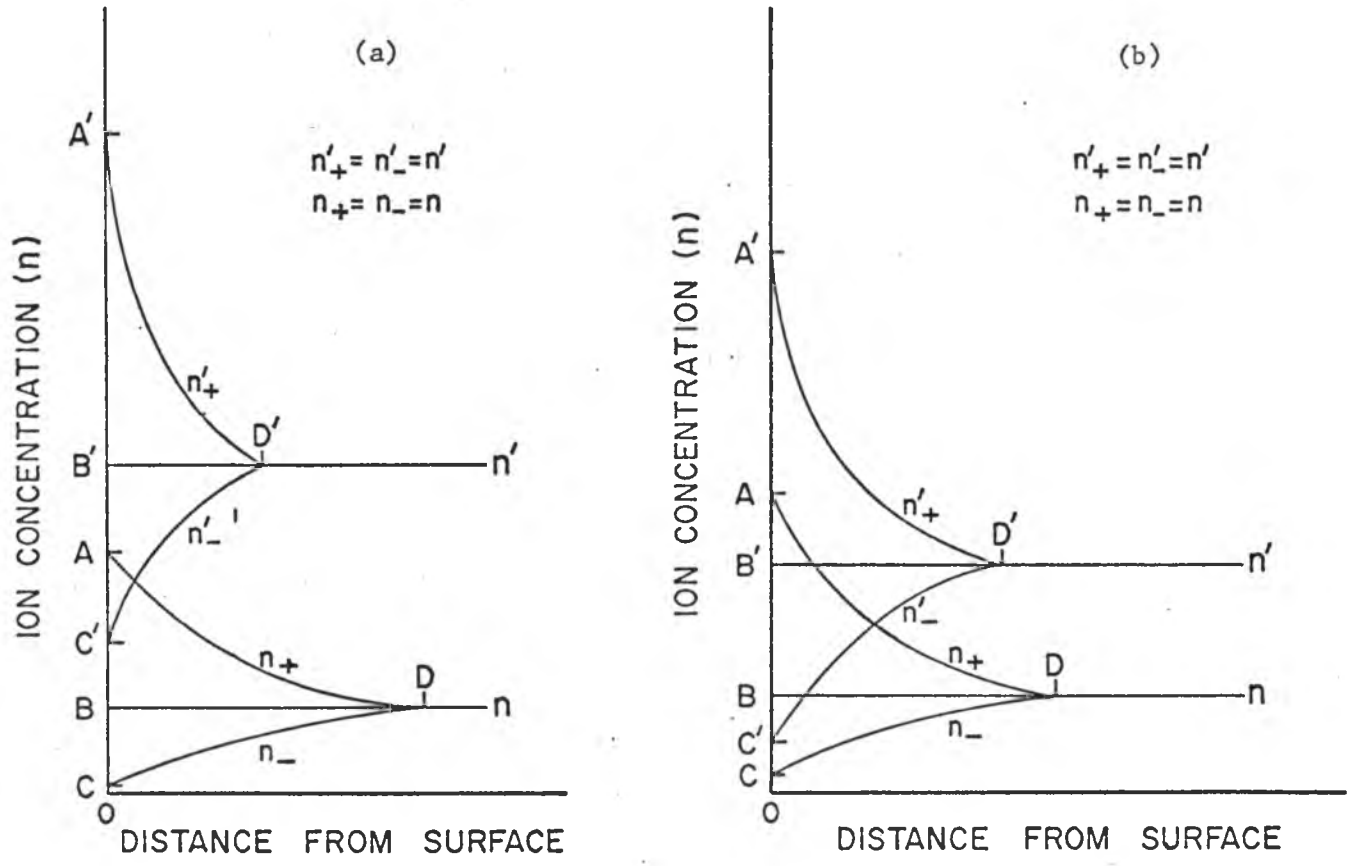

Figure 1. Charge distribution of the diffuse double layer of a negative particle at two electrolyte concentrations.

(a) Constant Surface Potential
(b) Constant Surface Charge

T = absolute temperature

For small surface potentials (<< 25 millivolts) the solution to the above equation may be written as:

$$\psi = \psi_o e^{-\kappa x}$$

where ψ_o = potential at surface

κ = debye-huckel reciprocal length

x = distance from surface

The potential has a maximum value at the surface and decreases roughly exponentially with the distance from the surface. There are actually two types of particle surfaces as regards to their potential behavior differences. The first is called the constant surface charge type. For this type of surface, the charge of the particles is determined by the interior lattice imperfections or isomorphous substitutions, and does not change with increasing electrolyte concentrations or pH. The diffuse double layer is compressed, however, and the surface potential decreases with increasing electrolyte concentration. The second type of particle surface is called the constant surface potential type. These are particles whose surface potentials are determined by the concentration of potential determining ions. The magnitude of this potential is not affected by the addition of an indifferent electrolyte (for example sodium chloride) so long as the concentration or activity of the potential determining ions are not affected by the presence of these electrolytes. For this type of double layer, computations show that the surface charge of the particles increases with increasing indifferent electrolyte concentration and the surface potential remains constant.

In the case of the constant surface potential type, in which the double layer is created by the adsorption of potential-determining ions, the potential is given by the Nernst equation:

$$\psi_o = \frac{KT}{\nu e \ln C/C_o}$$

in which, ψ_o = electric potential at the surface

K = Boltzmann constant

T = absolute temperature

e = electronic charge

ν = valence of potential determining ion

C = concentration of these ions

C_o = their concentration at the zero point of charge, when $\psi_o = 0$

Figure 2 shows the relationship between electric potential and the distance from the surface for both types of surfaces at two electrolyte concentrations.

The clay particles and the other particles in suspension are also attracted to one another through physical attractive forces as well as electrostatic forces. The stability of the colloidal system is thus dependent on the net result of the attractive and repulsive forces among the clay particles and other components in the colloidal system. According to Powis (in Kruyt's "Colloid Science," page 81), it is not necessary to destroy the charges of the colloidal particles completely in order to obtain flocculation as lowering the zeta-potential of the system to a critical value called the critical potential, would result in flocculation. It has been known that various factors like valency of

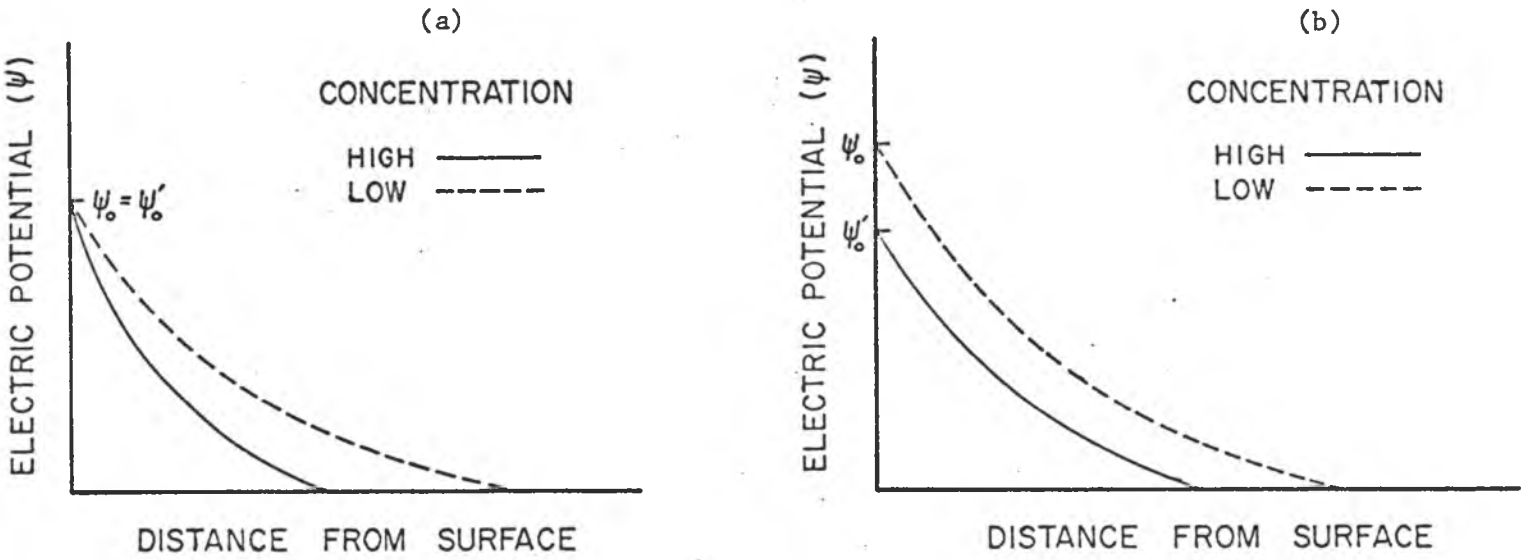

Figure 2. Electric potential distribution in the diffuse double layer at two electrolyte concentrations.

(a) Constant Surface Potential
(b) Constant Surface Charge

cations (following the Rule of Schulze and Hardy), electrolyte concentration, the pH, charge density of the particles, type and valency of anions present, and the nature of the colloids themselves affect the stability of the colloidal suspension. Following is an analysis of the attractive and repulsive forces that interact to produce stable or flocculated clay colloidal systems:

Forces of Attraction

1. Van der Waals Forces

These are the short range attractive forces (orientation, induction, and dispersion) resulting from the interaction between molecules. However, according to Kruyt (1952), van Olphen (1963), and Verwey and Overbeek (1948), the three attractive forces are cumulative and are also additive in all atoms or molecules in macroscopic particles such as clay minerals, thus resulting in an appreciable attractive energy. For two macroscopic particles, the attractive energy varies with r^{-2} and the attractive forces vary with r^{-3} (rather than r^{-6} and r^{-7}, respectively, for atoms or molecules).

2. Electrostatic (Coulombic) Forces

These are the attractive forces between particles of opposite charge. According to Coulomb's Law, the energy of attraction of these oppositely charged particles is proportional to the product of their charge magnitudes and r^{-1}, where r is again the distance separating the two charges. In clay minerals, due to isomorphous substitution, there is a net negative charge in the interior of clay lattices. However, there may be positive charges present on the edges of some clay particles due

to broken bonds between aluminum and the oxygen or hydroxyl ions. This is especially true in clay of kaolinite type. Under normal soil pH conditions, these edges would have positive charges, though they may become negative at higher pH. According to van Olphen (1963, 1964), there is a tendency for these oppositely charged clay surfaces and edges to be attracted due to Coulombic forces. These forces are of a long range type and can occur between different soil constituents. When such attraction occurs, the clay particles are said to be "mutually flocculated" (Schofield and Samson, 1954; and van Olphen, 1964).

3. Bridging of Particles by Polyfunctional Long-Chain Compounds

Van Olphen (1963) stated that polyfunctional long-chain compounds may become adsorbed on more than one particle simultaneously and thus bridge them together. It is expected that this mechanism explains, at least in part, the role of organic matter in stabilizing soil structure.

4. Bridging of Particles by a Second Immiscible Liquid Component

This fourth type of particle attraction was also explained by van Olphen (1963) in which particles dispersed in two immiscible liquids are agglomerated. In the presence of water the particles are enveloped by a film of the water and when two particles come together, the water films will flow together at the juncture points, reducing interfacial area and total free energy.

Repulsive Forces in Clay Particles

A. Short Range Repulsive Forces

1. Born Repulsion

When two atoms or molecules approach each other at very short

distance, the negatively charged electron clouds tend to overlap and thus cause the atoms or molecules to repel each other, and resist the interpenetration of the crystal lattices. However in most cases, and for practical distances of separation, the cumulative and additive attractive forces due to van der Waals attraction exceed that of Born repulsion. According to Pauling (1960) the energy of repulsion E_R is written as

$$E_R = \frac{Be^2}{r^n}$$

where E_R = repulsive energy

B = a proportionality constant

e = electronic charge

r = distance between atoms or molecules

n = an exponent, about 9, depending on the atoms or molecules involved

2. Short-range Hydration or "Lyosphere" Repulsion

These are the short-range forces which exist when two hydrated particles are approaching each other due to the energy needed to desorb the water or solvent molecules in order to allow the particles to come closer to each other. Such repulsion may occur in clay particles or cations in the double layer. Ions in the double layer may be hydrated and behave this way (van Olphen, 1954 and Low, 1968).

3. Dipole-Dipole Repulsion

When polar particles or molecules are oriented in such a way that the side of the molecules with similar polarity (charge) approach each other, then there is a repulsive force. Van Olphen (1954) suggested

that exchangeable cations in the hexagonal cavities of clay surfaces together may behave as dipoles with the negative charges within the lattice. When two such clay particles approach one another with the cations approaching each other, there is a repulsive force created.

B. Long Range Repulsive Forces

1. Entropic Repulsion

According to van Olphen (1963) this repulsion is due to steric hindrance in the layer of adsorbed surface active molecules at a distance close enough for interference. This force, according to him, is likely to be effective only for small particles at moderately large distances, since van der Waals forces of attraction for small particles at this distance is not too large. For large particles for which van der Waals attraction is stronger, another long-range double layer repulsion is necessary to stabilize the suspension.

2. Double Layer Repulsion

As explained again by van Olphen (1963) when two particles approach each other in suspension owing to their Brownian motion, their diffuse counter ion atmospheres begin to interfere which would lead to changes in the distribution of the ions in the double layer of both particles causing an increase in the free energy of the system. There is thus a pressure created to oppose this increase in energy, called the osmotic pressure. This repulsive osmotic pressure is equal to the difference in osmotic pressure between a plane midway between the surfaces and a point beyond the influence of the particles in the external solution (Low, 1968). In the presence of only a single

symmetrical electrolyte solution, the pressure developed between two parallel surfaces is given by the Langmuir (1938) equation as developed by Verwey and Overbeek (1948) and was also used by El-Swaify and Henderson (1967).

$$P_{osm} = 2n^{o}KT(\text{Cosh } u-1)$$

in which P_{osm} = net repulsive osmotic pressure

n^{o} = the number of ions per cm^{3} in the external solution

K = Boltzmann constant

T = absolute temperature

$$u = \frac{\nu e\, \psi_{d}}{KT}$$

where ψ_{d} = electrical potential at midplane between particles, and the other variables are as defined previously.

Further quantitative discussion for calculating u was given by Verwey and Overbeek (1948) and Norrish (1954) as follows:

$$\int_{Z}^{u} (2 \text{ Cosh } y - 2 \text{ Cosh } u)^{-1/2}, \; dy = -\kappa d$$

and $$\sigma = \left(\frac{n^{o}\varepsilon KT}{2\pi}\right)^{1/2} (2 \text{ Cosh } Z - 2 \text{ Cosh } u)^{1/2}$$

in which $y = \frac{\nu e\psi}{KT}$ and $Z = \frac{\nu e\psi_{o}}{KT}$

κ = Debye-Huckle reciprocal length ($1/\kappa$ = unit length)

d = half distance between neighboring parallel surfaces

ψ = electrical potential at a defined plane between surfaces

ψ_{o} = electrical potential at either surface

σ = surface charge density (esu/cm^2)

Further calculations and approximations of the above equations would finally enable us to plot u against d and hence P_{osm} against d. The plots would differ for various clay minerals, exchangeable ions or their combinations. Other factors that affect the osmotic pressure in the colloidal system are concentrations of cations and anions (n^o) and the valency of the cations and anion, ν.

Figure 3 shows the energy of repulsion V_R and of attraction V_A. The three solid curves for V_R are for the same particles or colloids at three different electrolyte concentrations. The dotted curve shows the energy curve of another type of colloid at an intermediate electrolyte concentration. Similarly, the two solid lines are for attractive energies of one colloidal system and the dotted curves are for another. Other short range repulsive and attractive energies are also present but are not shown on the diagram. The net interaction energy between the particles may be obtained by adding the energies together at a certain distance from the particle surface under a certain electrolyte concentration and by assigning arbitrarily a negative value to the attractive energy and a positive value to repulsive energy, i.e. $V_{net} = V_R + V_A$. If the resulting net energy is positive, the colloidal suspension is expected to be stable or to remain dispersed and if the resultant net energy is negative, it is expected that particles become flocculated.

Recent Studies on Aggregate Stability

Much work has been done on the assessment of stability of soil

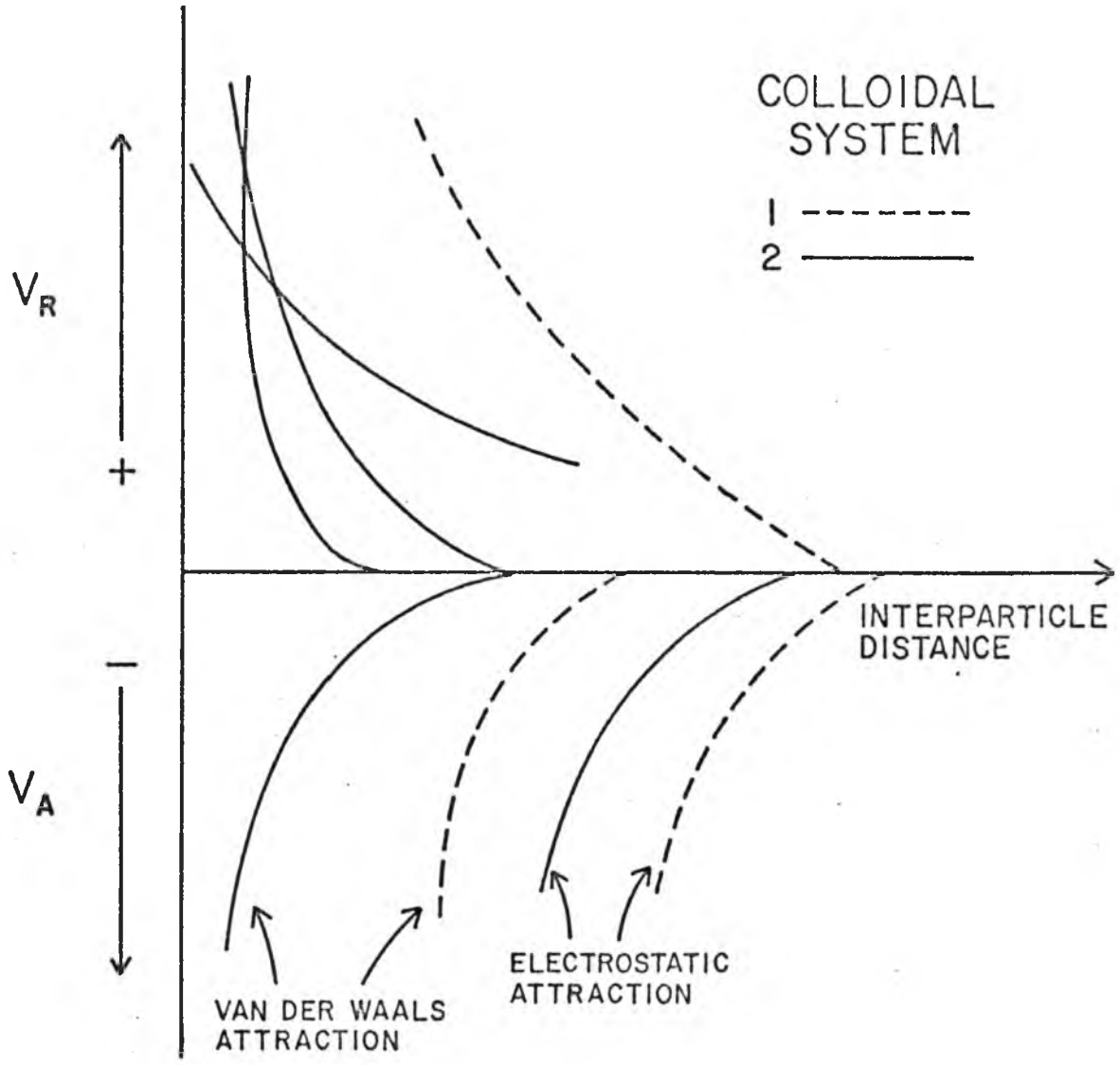

Figure 3. Schematic illustration of repulsive (V_R) and attractive energy (V_A) as a function of particle separation at three electrolyte concentrations and two colloidal systems 1 and 2.

aggregates in many parts of the world. A traditional method that was used and is presently used is the wet sieving technique. Another measurement that is used as an index of aggregate stability is the particle size analysis, also called the mechanical analysis. These techniques, though well standardized and give reproducible results, provide little insight into mechanisms responsible for aggregate coherence.

Many workers have tried to find the factors and mechanisms that are involved in enhancing or weakening of aggregates stability. Kemper and Koch (1966), for example, used regression analysis to show a good correlation of aggregate stability with factors such as organic matter content, presence of free oxides and hydroxides of iron and aluminum, exchangeable sodium, and clay content. Allison (1968) evaluated the status of present knowledge of soil aggregation with emphasis on the role played by higher plants, microorganisms and their synthesized polysaccharides and humus by-products. He distinguished aggregate formation from aggregate stabilization and proposed that aggregates are formed chiefly by physical forces, whereas the particles within aggregates are held together (stabilized) by organic polymers. He also believed that oxides of iron and aluminum have an important role in aggregate stabilization, together with coating of clay skins.

In 1954, Pereira made an extensive comparison of various methods of assessing the structure of tropical soils. He found that wetting by rainfall impact on dry crumbs gave the best wet-sieving tests on clay soils. Wetting by immersion in water gave some differences between treatments. On soil cores, he used measurement of total pore-space, and

field capacity showed no correlation with field behavior of soil, while percolation rate, free-draining pore-space and a new rainfall acceptance test did show correlations. He also used dry-sieving of clods in the field as an index of structural quality.

Hydraulic conductivity of soils has been used frequently as an index of stability of soil aggregates on the dispersion behavior of soil colloids. Using this as an index, many factors that affect the aggregate and colloidal stability of soils may be compared.

Relative behavior of montmorillonitic and kaolinitic soils has been much studies. Naghshinehpour, et al. (1970) for example, found that, at low electrolyte concentration and high SAR (sodium adsorption ratio), montmorillonite soils had decreased hydraulic conductivity. Among montmorillonite clays, those with more iron oxide content were more stable than those with less. The latter also had decreased hydraulic conductivities at very low electrolyte concentration and high SAR. McNeal (1967) and many others made similar observations.

Many studies also have been done on the relative effects of cations on hydraulic conductivity of soils. It has generally been found that stability of soils decrease in the following order of cations Ca $\geq$ Mg > K $\geq$ Na (Gazdar, 1969; Elgabali, et al., 1970; Mazurak, 1953, among others). Flocculation of soil colloids by cations are also in the above order agreeing with the Rule of Schulze and Hardy.

El-Swaify (1970) measured the stability of surface and subsurface samples of Molokai and Kawaihae soils (consisting mainly of kaolins, iron oxides, gibbsite and amorphous constituents) by the wet-sieving method after equilibrating them with seawater and its dilutions (25 and 100

times), salt concentration ranging from 0 to 0.61 N, and 0.61 N homoionic $MgCl_2$, $CaCl_2$, and NaCl solution. Results showed these chemical treatments produced no structural changes in the surface or subsurface soil used in the study. This was attributed to the mineralogical composition of the soil and its charge characteristics. El-Swaify, et al. (1970) found that under certain conditions, potassium gave the lowest dispersion in contrast to what was previously found. This was attributed to the specific adsorption of K by the clay surfaces in a manner that would not be predicted by the Schulze-Hardy rule.

Quirk and Schofield (1955) defined the "threshold concentration" for an electrolyte as the concentration below which 10 to 15 percent decrease in permeability was noted. For soils that contained kaolinite, illite, vermiculite, and were saturated with the respective cations of the salt solutions, the threshold concentrations for NaCl, KCl, $MgCl_2$, and $CaCl_2$ were 0.25 M, 0.067 M, 0.001 M and 3×10^{-4} M, respectively. In flocculation series studies, they found that soils rich in illite, kaolinite and vermiculite and saturated with Ca, were partially flocculated at 0.001 M $CaCl_2$, and completely flocculated at 5×10^{-4} M $CaCl_2$. Though it has been generally agreed that increasing electrolyte concentration would increase flocculation, some exceptions have been noted (van Olphen, 1956; Cashen, 1959; and Dangler, 1973).

Nakayama (1966) used Na-salts to study the deflocculation effects of anions on soil materials which was mostly montmorillonite. Dispersion of various soils was in the order $(NaPO_3)_6 \geq Na_2CO_3 > Na_2SO_4 = NaCl$. He found that while NaCl and Na_2SO_4 treatment resulted in flocculation of the particles with increasing treatment rates (concentration) Na_2CO_3 and

$(NaPO_3)_6$ treatments increased the deflocculation.

The effects of anions on structure of Hawaiian soils using hydraulic conductivity as an index was also studied by El-Swaify (1973). For Molokai soils, while solution concentration has significant effects on hydraulic conductivity, the anion type seemed to significantly increase hydraulic conductivity of the soil in the following order: $SiO_8^{=} < HCO_3^{-} < SO_4^{=} < Cl^{-}$ and this order was also correlated with decreasing pH in their respective systems. Surface Kawaihae soil was also affected only by solution concentration, but for subsurface soil, Cl^{-} has significantly different effects from the other three anions which have about the same effects on the hydraulic conductivity. Hilo soils, consisting mostly of amorphous silicates, showed high responses to anion types especially for the surface soils which depends lowest on electrolyte concentration. There was little distinction between $SO_4^{=}$, HCO_3^{-}, and $SiO_3^{=}$ in the subsurface soils. On Lualualei soils (mostly 2:1 clays), effects of solution concentration had more significant effects than anion types, due to its permanent charge characteristic.

Quirk (1950) found that where the effects of cultural treatments on the structure of soil were being considered, shaking for short periods of 5 minutes gave more reproducible results than for 20 minutes. Capillary wetting was found to be more satisfactory than flood wetting because flood wetting caused greater breakdown, but should be a good simulation of water entry in surface soils during flood irrigation. Machine shaking was also more preferred to hand shaking during stability measurements.

Dry soil crumbs, when immersed in water tend to break up or slake into discrete fragments. This breakup may proceed further with the clay

particles going into suspension (dispersion). The two main causes of slaking are due to explosions of entrapped air in the aggregates (Yoder, 1936) and shear stresses due to swelling (Henin, 1938) or differential wetting or incipient failure (Quirk and Panabokke, 1962). Emerson (1962) noted that entrapped air was the primary cause of slaking of kaolinite, while illite flakes slaked only when air was present initially, but slaking was due to both swelling and entrapped air. He also found that montmorillonite flakes dried over phosphorus pentoxide, did actually slake on immersion in water; however, the edges of the flakes became frayed and there were many transverse cracks and flakes evacuated before flood wetting swelled to the same extent.

Panabokke and Quirk (1957) studied the effect of initial water content on the stability of aggregates in water. They observed that soil aggregates were most stable at pF 2-3 before wetting (pF is a symbol used to represent soil moisture suction or tension and is defined as an exponential expression of a free-energy difference based on height of a water column, h, in centimeters, above free-water level; thus pF = $\log_{10}$h). If they were first wet to pF 2, and then slowly wet to lower tensions before immersing in water, the stability of the aggregates was the same as at pF 2. Decreases in stability of aggregates at pF drier than pF 2 were attributed to more rapid wetting. At pF > 5 (at about oven dry moisture content) aggregates became stable again, the reason given was due to action of entrapped air which prevents direct contact of the water with some of the colloidal surfaces.

Later in 1962 Quirk and Panabokke studied the incipient failure of soil aggregates of virgin and cultivated soils. They compared the

relative stabilities of the soils under two sets of experimental conditions. In one method, the soils were first wetted from dry conditions to 30 cm of suction and then to 2 cm suction. In the second method, the wetting was carried out directly to 2 cm suction. Both soils were found to behave almost identically by the first method, but the virgin soil was apparently more stable than the cultivated soil by the second method. This was attributed to the role of organic matter in strengthening the pores against failure.

In 1968, Emerson used the water content for dispersion of clay from soil aggregates as an index of aggregate stability of natural and treated soils. He proposed that dispersion of clay mixtures and of oxidized soils (organic matter removed) depends on the spacing between the clay crystals before being immersed into water. When comparing the length of time of remoulding of the clays and oxidized soil aggregates, he found that longer remoulding time at the same moisture content does not increase dispersion. Dispersion of natural aggregates increased with continued remoulding and was attributed to breakdown of bonds between clay crystals. The presence of organic matter increased susceptibility of remoulded aggregates to dispersion probably due to broken bonds linking clay crystals together, but the more strongly the bonds due to organic matter holding the particles together, the more remoulding is required to produce dispersion. Presence of Al^{3+} ions on the clay surface increases the water content for dispersion, i.e. the stability of the aggregate is increased.

Many workers, among them Blackmore (1973), Deshpande, et al. (1964), Kemper and Koch (1966), Allison (1968), and El-Swaify, et al. (1975)

found that the presence of iron and aluminum oxide or hydroxides help stabilize the structure of aggregates due to bonding action of these oxides physically or due to electrostatic attraction. El-Swaify and Emerson (part I, 1975) found that Al was more effective than Fe both in reducing the swelling and slaking of clay disks and in increasing clay resistance to dispersion in pyrophosphate solutions.

Considerable work also has been done on the effects of exchangeable cations on the stability of soil aggregates. It has generally been found and agreed that for a homoionic system, the aggregates are more stable according to the following order: $Na \leq K < Mg \leq Ca$. Composition of the exchangeable cations, especially the exchangeable sodium percentage (ESP) has also been found to affect the aggregate stability of the soil very much. Increasing ESP are correlated with decreased stability. Bakker, et al. (1973), for example, noted that moisture content for minimum dispersion of remoulded soil was lower in Na-Mg soils than Na-Ca soils by about half times. This was attributed to higher hydration energies of Mg than Ca (about 20% more). Another probable reason given was that in water, more Mg^{++} move into the double layer than Ca^{++} thus increasing repulsive energy. Emerson, et al. (1973) studied the spontaneous dispersion of aggregates in water. Similar results were obtained with regards to dispersion characteristics of soils in relation to exchangeable cations. The ESP required to induce dispersion was higher for Na-Ca soils than for Na-Mg soils. It was also found that soils with about the same amount of total exchangeable bases dispersed at the same ESP and others which do not disperse at the same ESP were attributed to the presence of Al^{3+} on the exchange complex.

In the same studies they found also that water uptake (swelling) of the Na-Mg soil was higher than Na-Ca soil at the same ESP, due to increased amount of Mg^{++} in the double-layer thus increasing the swelling pressure. If aggregates were first wetted under suction and then flooded with water, they did not disperse. This was attributed to reduction in ESP due to diffusion of Na into solution. However, the measured reduction (from 7 to 5.8) in ESP was not sufficient to account for the subsequent lack of dispersion in water. Finally Emerson and his coworkers proposed mechanisms of spontaneous dispersion of aggregates in water. Two conditions should be met before clays containing a small amount of exchangeable sodium disperse. First, the concentration of external soluble salt should be lower than the flocculation value of the clay, and the second condition is that the gradient of the soluble salt concentration at the boundary of an aggregate has to exceed a certain value which is equivalent to the shear stress.

Emerson (1967) classified soil aggregates into eight classes based on their coherence in water, using slaking and dispersion behavior of the soil aggregates according to the following criteria: immersion of dry aggregates in water, immersion of wet remoulded aggregates in water, and suspension of aggregates in water. One further class was distinguished by the presence of carbonate. The classification scheme proposed by Emerson is as in Figure 4. Though qualitative, these tests can be done in the field. Separation of aggregates is first made according to whether the dry aggregates break up (slake) when immersed in water, due to either stresses induced by entrapped air or swelling or both. These aggregates are classified into classes 1-6. Other

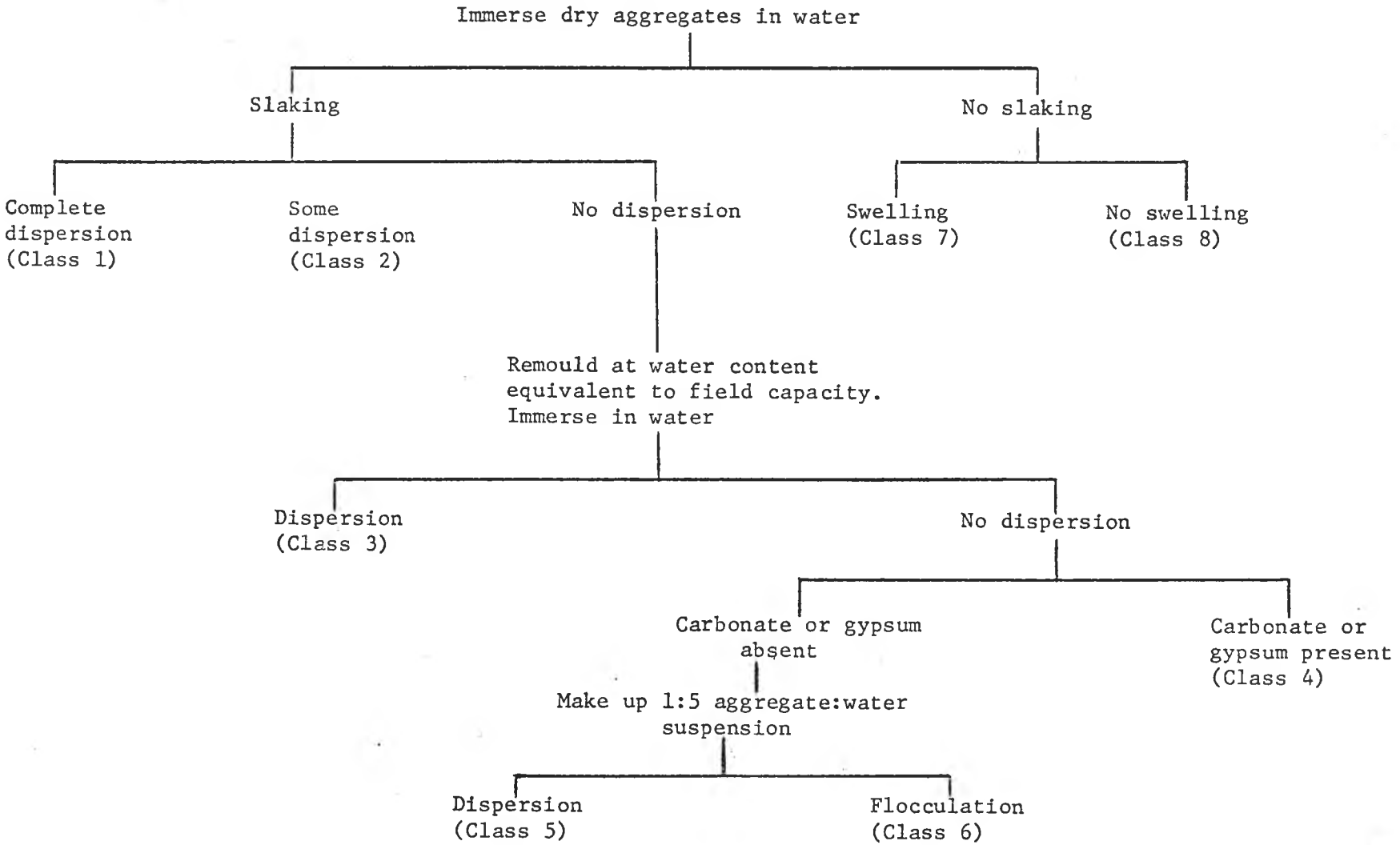

Figure 4. A classification of aggregates based on their coherence in water (Emerson, 1967).

aggregates are divided into class 8 in which aggregates are unchanged, or into class 7 in which aggregates swell but remain coherent. Aggregates placed in classes 1 and 2 are based on the effect of osmotic stress on them. As soluble salts initially present in the aggregates diffuse out when they are immersed in water some aggregates may undergo a change. If the stress is sufficient, the aggregates may disperse. Aggregates that appear to disperse completely are placed in class 1, while those that disperse partially in class 2. Aggregates that slake but do not disperse are placed in classes 3 - 6. Class 3 aggregates were defined as aggregates that, after remoulding at a water content equivalent to field capacity dispersed when immersed in water. This may be seen as a simulation of mechanical disturbance of the wet soil in the field. The aggregates that do not disperse after remoulding at field capacity and contain such soluble minerals as calcite or gypsum are placed in class 4. Thus this class includes soils that may contain minerals which dissolve rapidly enough to maintain the divalent ion concentration above the flocculation value. Aggregates that disperse at a water content intermediate between field capacity and that of a suspension (1:5 aggregate-water ratio, 10 minutes shaking) form class 5. If a suspension of aggregates flocculates completely after 5 minutes standing, they are placed in class 6.

Loveday and Pyle (1973) modified the Emerson test (Emerson, 1967) to relate a more quantitative measurement of dispersion in relation to ESP and hydraulic conductivity. Instead of merely observing if there is dispersion or not as natural or remoulded aggregates are immersed in water, they assigned scores of 0 to 4 to the degree of dispersion of the

aggregates after 2 and 20 hours of observation. A score of 0 means there is no dispersion, and a score of 4 means that there is complete dispersion, leaving only sand grain in a cloud of clay. For those air-dried soils which did not disperse when immersed in water (the score is 0), remoulding was recommended at moisture content equivalent to 100 cm suction. The dispersion index (D.I.) was calculated by adding the scores for air-dried aggregates to those of aggregates remoulded at moisture content equivalent to 100 cm suction. The possible range of dispersion index scores is 0-8. For those air-dried soils that disperse, a dispersion index was also calculated the same way but added to 8, so possible scores are now 9-16. A dispersion index was also scored on soils with known ESP. They reported a good relationship between D.I. and ESP, although there was considerable variance due to other factors. It was also noted that for soils whose D.I. was 8, the hydraulic conductivity was poor. It was suggested that the D.I. is useful because it is less time consuming than the measurement of hydraulic conductivity of soils, and allowing simple practical estimates of the stability of soil aggregates in the field.

MATERIALS AND METHODS

1. The Soils

The soils used for this study were from the islands of Oahu and Hawaii, chosen to represent different mineralogical composition and their requirement of or suitability for irrigation. Soil samples used were those that were also collected by Sinanuwong (1972) for research in her Ph.D. dissertation. The soil series sampled were:

1. Molokai silty clay, formerly classified as a Low Humic Latosol, now classified as a member of the clayey, kaolinitic isohyperthermic family of the Typic Torrox. Samples were collected from the Ap layer (0-15 inches) and from B_2 horizon (15-30 inches deep); and were assigned the symbols M_1 and M_2, respectively.
2. Lualualei clay, formerly classified as a Dark Magnesium Clay, now classified as a member of the fine, montmorillonitic isohyperthermic family of the Typic Chomusterts. Samples were collected from two different sites:
   (a) At the Naval Radio Station in Lualualei valley where three horizons were obtained. They are A_{11} (0-1 inches deep), A_{12} (1-10 inches) and A_c (10-20 inches). They will now be referred to as Lualualei soils and given the symbols L_1, L_2, and L_3, respectively.
   (b) From the Kokohead area near the Hawaii Kai Golf course, two horizon samples were collected, namely A_1 (0-2 inches) and A_{11} (2-12 inches). These samples will now be referred

to as Lualualei from Kokohead soils to which the symbols LK_1 and LK_2, respectively were assigned.

3. Honouliuli clay, formerly classified as a Grey Hydromorphic, now classified as a member of the very fine, halloysitic, isohyperthermic family of the Typic Chromusterts. Two horizons, A_p and B_2 at depths of 0-15 inches and 15-26 inches respectively were collected. The symbol H_1 and H_2 were assigned to the two horizons, respectively.
4. Kawaihae very fine sandy loam, formerly classified as Tropical Red-Deserts, now classified as a member of the medial isohyperthermic family of the Typic Camborthids. Samples were collected from A_1 (0-6 inches) and B_2 (6-15 inches) horizons and the symbols K_1 and K_2 respectively were assigned.
5. Ewa clay, formerly classified as a Low Humic Latosol, now classified as a member of the fine halloysitic isohyperthermic family of the Aridic Haplustols. The horizons sampled were A_p (0-13 inches) and B_2 (13-18 inches) and were given the symbols E_1 and E_2, respectively.

The mineralogical composition of the soils as analyzed by x-ray diffraction and their organic matter contents are shown in Appendix A. The CEC (as q_0), surface areas, and pH of the homoionic soils are given in Appendixes B, C, and D, respectively (after Sinanuwong, 1972).

II. Methods

A. Aggregate Stability Studies

1. Preparation of Homoionic Soils

Collected samples were dried, mixed, and passed through 5 mesh sieve and packed in large Buchner funnels. Homoionic Ca-, Mg-, K-, and Na-soils were then prepared by leaching with 1N $CaCl_2$, $MgCl_2$, KCl, and NaCl solutions, respectively. The leaching was continued until the leachates were identical in composition to the applied solutions. This was ascertained by testing for several ionic species contained in the untreated soils. Excess electrolytes were removed by distilled water washing for Ca and Mg soils, and by alcohol washing for K-, and Na-soils until a negative test for chloride was obtained by using 0.1 N $AgNO_3$. The homoionic electrolyte free samples were then air-dried, stored in airtight containers and moisture contents were determined.

2. Obtaining Standard Curve of Clay Concentrations Versus Turbidity

Na-soil aggregates of each soil type were wet overnight and were then dispersed by using the blender. The blended suspension was passed through a 53 μ sieve, keeping only particles of that size or smaller. The concentration of this suspension was determined gravimetrically. Suspension of concentrations ranging between 0 to 0.08% were prepared from the above suspension. Turbidity is an expression of the optical property of a sample in suspension which causes light to be scattered and absorbed rather than transmitted in straight lines through the sample. According to "Standard Methods," the Jackson candle Turbidimeter is the standard instrument for the measurement of turbidity, and the Jackson Turbidity unit (JTU) is the standard unit of measurement and expression of turbidity (Hach Laboratory Turbidimeter, Instruction Manual). Thus the prepared concentration of soil suspensions was read

as turbidity, in JTU, using the Hach Laboratory Turbidimeter (Model 2100). This instrument was based on the Jackson Candle Turbidimeter and calibrated using a series of standard concentrations of Formazin with assigned turbidity values in JTU. As an illustration, Figure 5 shows such a studied curve obtained for Molokai B soil.

3. Classification of Natural Soil Aggregates

Natural soil aggregates were classified according to their coherence in water using Emerson's classification scheme and procedures (1967) with slight modification. The following are the procedures used in the Classification scheme:

a. Stability of air-dry aggregates in water

About three of the air-dry aggregates of sizes between 2-4 mm were placed in a beaker containing 50 ml of distilled water. For Kawaihae soils, however, it was difficult to obtain aggregates of the above size because they easily break into small particles, so larger aggregate sizes than the above were also used. Stability of the aggregates in terms of slaking or dispersion was observed and recorded at 0 hour, 24 hours, and 48 hours, in duplicates. A scoring scheme similar to the one used by Loveday (1973) was adapted to describe the degree of slaking or dispersion. Numbers from 0 to 5 were arbitrarily assigned to the visual extent of slaking or dispersion of the aggregates. 0 signifies no slaking or dispersion and 5 signifies complete slaking or dispersion. The moisture contents of the air dry aggregates were also determined.

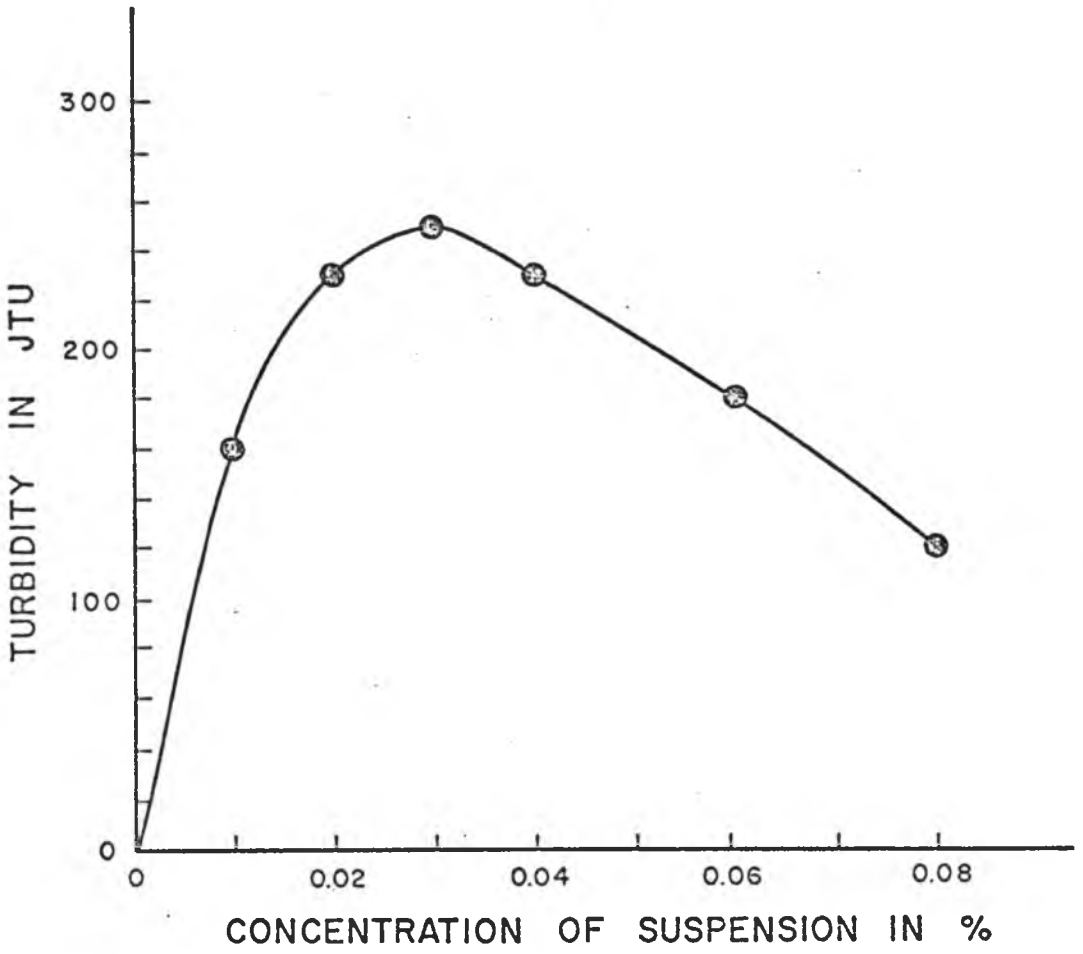

Figure 5. A standard curve of turbidity versus clay concentration for Molokai B_2 soil.

b. Dispersion of natural soil aggregates remoulded at about field capacity

About 2 ml of distilled water was added to 10 gm samples of natural soil aggregates so as to have a moisture content of about the field capacity of the soils (about 30%). The wetted samples were then remoulded for one minute with a small spoon, spatula, or rubber stopper with a glass handle, as appropriate. Remoulded subsamples were placed in a beaker containing 50 ml of distilled water in triplicate to determine the degree of dispersion after 24 hours. Another remoulded subsample in duplicate was taken for moisture content determinations. Dispersion of the remoulded aggregates in distilled water was taken after 24 hours. The liquid above those aggregates that showed dispersion was stirred gently with a glass rod so as to bring all dispersed particles into suspension. Their concentration was measured as turbidity using the turbidimeter. All turbidity samples were returned to their respective beakers. The contents of the beakers were then fully dispersed using the Biosonic III ultrasonic disperser (vibrator). The turbidity or concentration measured for the dispersed samples was taken as the total silt plus clay concentration in the sample. The ratio of the dispersed clay after 24 hours to this total clay plus silt content will be defined

as the "Dispersion Index" (D.I.).

c. Dispersion of 1:5 soil-water suspension

This is the third step in Emerson's method of classification of aggregates (Fig. 4). Twenty-five ml of distilled water was added to 5 gm samples of natural soil aggregates in a beaker and the contents were stirred with a glass rod for 10 minutes. The suspensions were left to stand for 5 minutes after which the Dispersion Index of the dispersed suspension was measured as in the previous method.

4. Effects of Prewetting on Breakdown of Aggregates in Water

Soil aggregates of sizes between 2-4 mm were placed in sintered glass funnels and were subjected to (hanging water column) suction or wetting of 100 cm. (As previously mentioned, it was difficult to obtain the above aggregate sizes for Kawaihae soil samples, so some samples were smaller or bigger than 2-4 mm.) The moisture contents of the soil aggregates were taken periodically until they became constant when equilibrium was expected to have been reached after about 7 days. At equilibrium, a few aggregates of each soil type were placed in a beaker containing 50 ml of distilled water. The stability of the wetted aggregates was observed and recorded from time to time until 48 hours or when further breakdown had stopped. The visual extent of slaking or dispersion was again assigned as a number from 0 to 5 signifying no slaking or dispersion to complete slaking or dispersion, respectively. If there was dispersion, the liquid above the aggregates was gently stirred so as to bring the dispersed particles into suspension. The

Dispersion Index of the suspensions was measured by using the turbidity readings of these samples and standard curves. The suctions were then reduced to 50 cm, 30 cm, and 15 cm, taking samples for stability tests at equilibrium at each suction. New samples were added each time the suction was lowered to the next lower step.

5. Dispersion of Homoionic Soils Remoulded at Different Moisture Contents

Distilled water (1, 2, 3 and 4 ml) was added separately to 5 gm samples in a small beaker. The wetted samples were then remoulded for one minute. Duplicate subsamples were scooped from each sample with a spatula and placed in a beaker containing 50 ml of distilled water. Remoulded subsamples in duplicates were also oven dried for moisture content determinations. Samples in the 50 ml distilled water were left overnight before Dispersion Index was determined. Dispersion Index versus Moisture Content curves were plotted.

6. Dispersion of Natural Aggregates at 50 cm Suction in .001M and 0.1M Sodium Pyrophosphate Solution

Natural aggregates of surface soils were equilibriated at 50 cm distilled water suction as previously described. The equilibriated samples were then immersed in beakers containing 50 ml of 0.001M sodium pyrophosphate solution, left overnight and followed by Dispersion Index determinations. To another sample, 50 ml of 0.1M pyrophosphate solution were added and allowed to stand overnight, after which the pyrophosphate solution was siphoned out, 50 ml of 0.001M sodium pyrophosphate was slowly added to the aggregates, left overnight, and the Dispersion Index was again determined.

B. Colloidal Stability Studies

1. Preparation of Stock Suspensions

Water was added to the homoionic soil samples, left overnight and dispersed by using the blender. Clay suspension of 53 μ or smaller was collected as the stock suspension using a 270 mesh sieve. The clay plus silt concentrations of these suspensions were determined gravimetrically.

2. Flocculation Series Tests

Flocculation series tests were done on each homoionic soil horizon of all soils to determine the Flocculation Value, defined here as the concentration of a certain electrolyte which flocculates a stable clay suspension by a certain degree. The electrolytes used on respective homoionic soils were chlorides, nitrates, carbonates, or bicarbonates of Ca, Mg, K, and Na. The procedure was as follows:

Different amounts of the electrolytes were added to clay suspensions in 50 ml culture tubes (size 150 X 25 mm with screwcaps) so as to have a final clay concentration of 0.02% for Molokai soil, and 0.04% for other soil types and so as to have varying final electrolyte concentrations. The stated clay concentrations are the maximum concentrations of the clay that fall within the near-straight-line part of the standard curve of clay concentration versus turbidity. When electrolyte was to be added to the suspension, the addition was made before making up to full volume. Visual observation was made and turbidity was taken for < 2 μ particles in fully or partially stable systems at appropriate times and depths. A graph of turbidity (clay concentration) versus electrolyte concentration was then plotted for

each flocculation series. The flocculation value was then chosen from the graph. The pH values of suspensions were also recorded.

3. Exchangeable Sodium Percentage (ESP) and Exchangeable Potassium Percentage (EPP) for Dispersion/Flocculation

Appropriate amounts of Na-saturated soil were added to Ca-saturated soil suspensions so as to have a mixture of soil that had an ESP of 5, 10, 15, 25, 50 and 75 in $NaCl:CaCl_2$ solutions. Appropriate calculations were made using respective regression equations or exchange isotherms ($\frac{q_{Ca}}{q_0}$ versus $\frac{C_{Ca}}{C_0}$) of Sinanuwong (1972). These were done at three electrolyte concentrations of 0.1 N, 0.01 N and 0.005 N. A similar procedure was followed with Mg instead of Ca as the complementary cation to Na. For Honouliuli, Lualualei, and Lualualei from Kokohead soils, suspension mixtures with EPP of 5, 10, 15, 25, 50 and 75 were also prepared similarly with Mg and Ca as the complementary cations to K, resulting in final electrolyte concentrations of 0.1 N and 0.01 N. The final clay concentrations in the mixtures were again maintained at 0.02% for Molokai and at 0.04% for other soils. The contents of the tubes were then shaken and set aside until all particles greater than 2 μ had settled down at appropriate time and depth (3.5 hours for 5 cm). Visual observation was made for flocculation or dispersion and then the turbidity of the suspension was measured to determine the < 2 μ clay concentration remaining in suspension if any. The pH's of the suspensions were also taken. A plot of the turbidity (or clay concentration) versus ESP or EPP was made for each soil horizon and at the three stated electrolyte concentrations and the ESP or EPP at which the suspensions were flocculated was recorded. As an illustration Figure 6 shows such a plot and Figure 7 shows similar curve but with an inflection point.

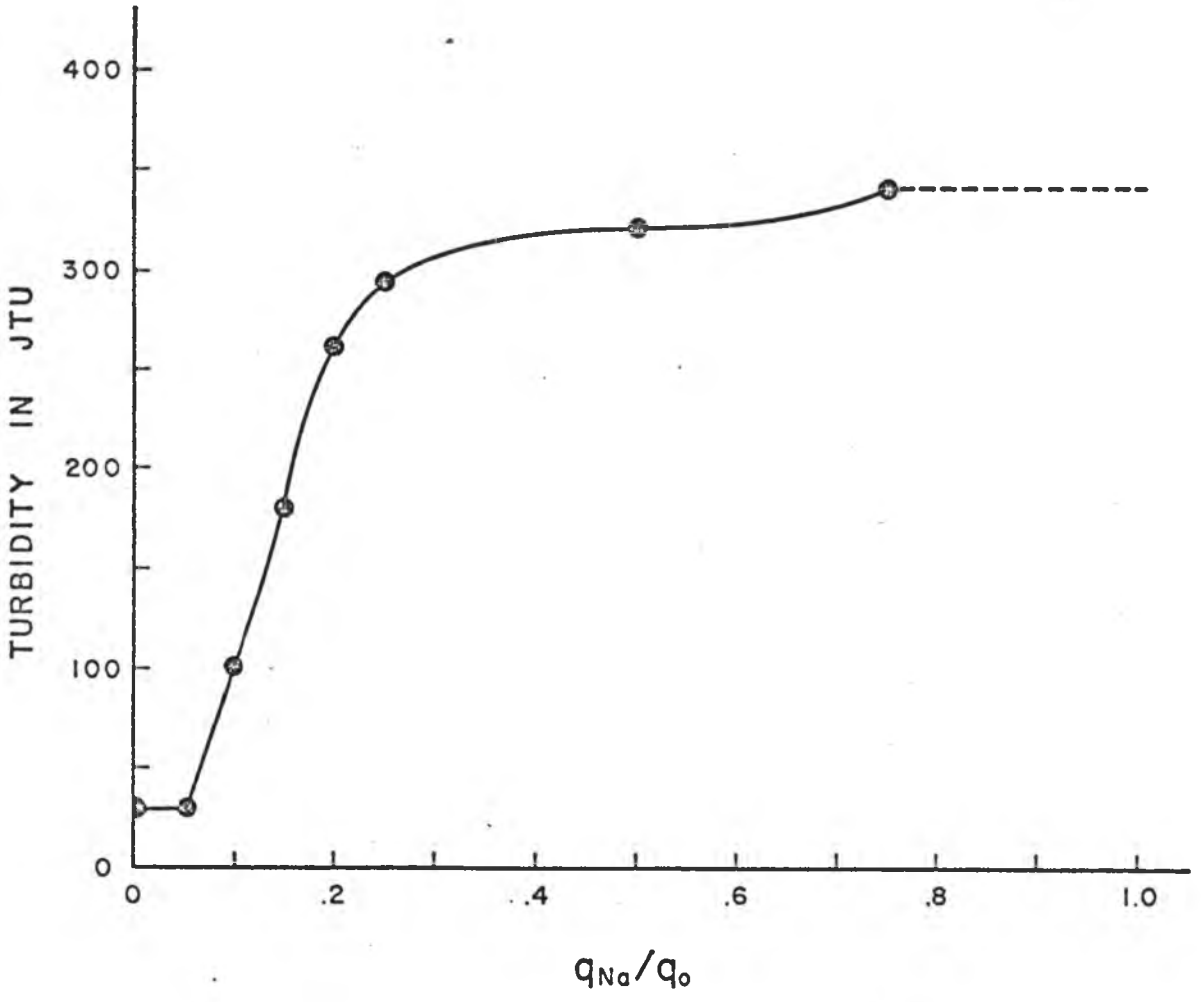

Figure 6. A plot of turbidity (JTU) versus ESP for Ewa B_2 suspension in 0.005 N (Na-Ca) electrolyte concentration.

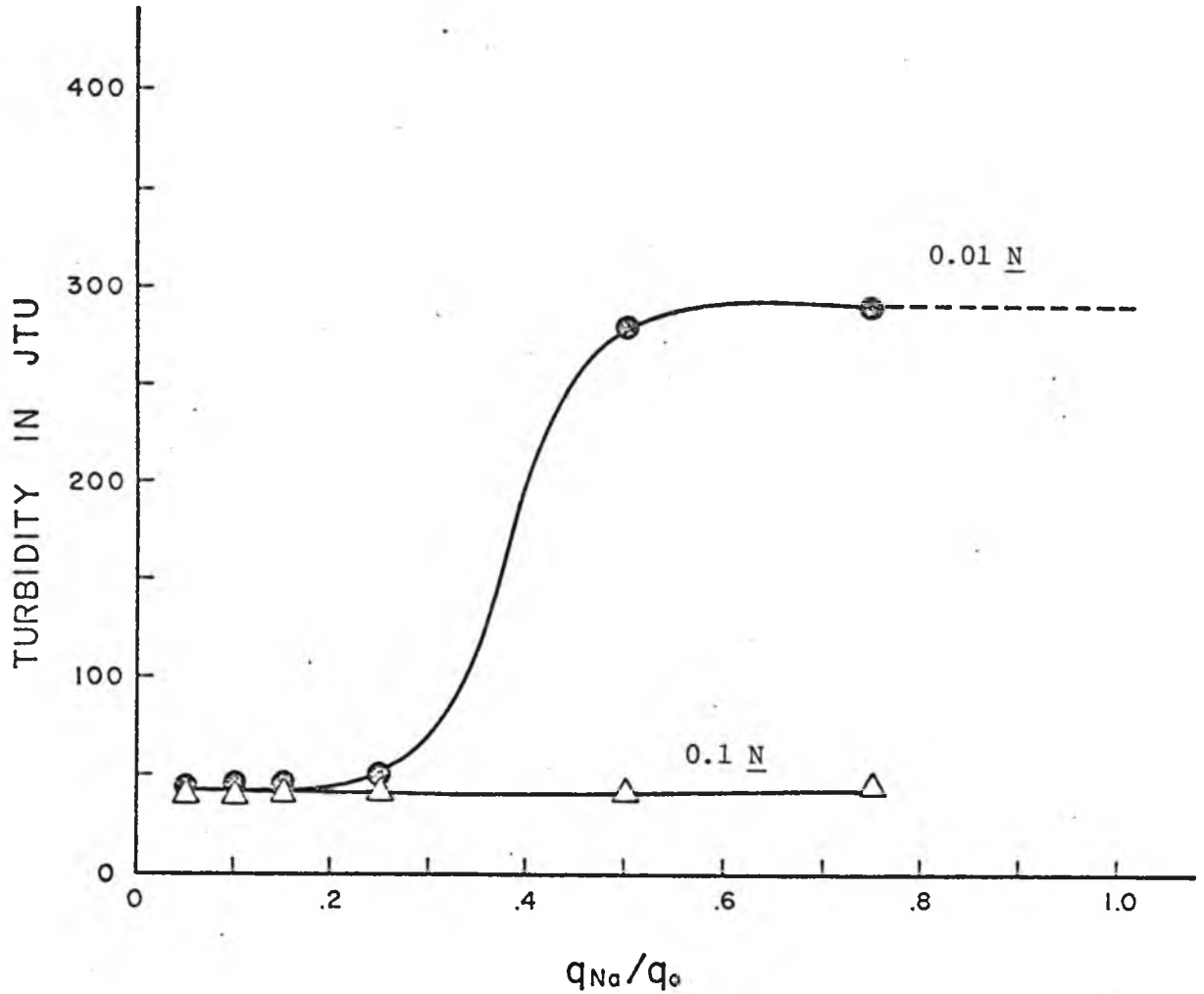

Figure 7. A plot of turbidity (JTU) versus ESP for Honouliuli B_2 suspension in 0.01 N and 0.1 N (K-Ca) electrolyte concentration.

RESULTS AND DISCUSSION

I. Aggregate Stability Studies

A. Classification of Aggregates According to Emerson's Scheme of Classification (1967)

As shown in Table 1, all the air dry soil aggregates slaked in distilled water, but to a different degree. While other soils did not disperse, the Lualualei soil from Kokohead did. The Ewa soil, with an initial (air dry) moisture content of 10.0% seemed to be the most stable among the five soil types with a degree of slaking of 1. Stability was then followed by Kawaihae, Molokai, Honouliuli, and Lualualei. It was observed that all aggregates slaked mainly due to the explosions of entrapped air, though "explosions" were noted to a lesser degree in the Kawaihae soil, which actually did not have aggregates similar to those of other soils. (It was difficult to get aggregate sizes between 2-4 mm for the Kawaihae soil because they are unstable even in the field.) The Molokai soil was shown to slake to about the same degree as the Honouliuli soil after 48 hours, though initially the Molokai slaked only to the degree of 2. It was expected from previous studies by other workers, and also from its mineralogical composition, that the Molokai should be more stable than the Honouliuli, which was not so in this experiment. This may be due to the lower water content in the Molokai aggregates compared to those of the Honouliuli soil, which may have caused them to undergo more severe incipient failure. The Lualualei soils behaved a little differently depending on the source of the sample. The one from Kokohead slaked only to the degree of 1,

Table 1. Slaking (S) and Dispersion (D) of Air-Dry Aggregates in Water

Soil type	Moisture content of air dry aggregates (%)	Slaking or dispersion in distilled water*					
		0 hr		24 hr		48 hr	
		S	D	S	D	S	D
Molokai A_p	3.56	2	0	3	0	3	0
Honouliuli A_p	7.53	3	0	3	0	3	0
Ewa A_p	10.09	1	0	1	0	1	0
Kawaihae A_1	4.37	0	0	2	0	2	0
Lualualei A_1	8.10	4	0	4	0	4	0
Lualualei A_1 (Kokohead)	11.70	1	0	1	1	1	1

*Rating based on a scale from 0-5 in increasing slaking or dispersion order.

but was also dispersed on the fringes of the swollen aggregates after 24 hours. The initial moisture content of these samples were higher than those from the Naval Station, which in addition to the mineralogy of the soils, may explain the difference.

Since the soils slaked, they would be classified under classes 1 to 6 (Figure 4). Assignment to individual classes depends on whether they disperse in 1:5 soil-water suspension after stirring with a glass rod for 10 minutes. None of the soils could be classified under class 1 since they did not disperse completely in distilled water; however, the Lualualei from Kokohead was classified into class 2 since it showed some dispersion.

When the yet unclassified soils were remoulded at approximately field capacity (30% moisture content), all soils except the Molokai A_p dispersed in distilled water, as shown in Table 2. The Honouliuli soil seemed to be most dispersed with a dispersion index of 38.2% while the others were below 10%. According to Emerson's classification scheme, all these soils namely Honouliuli, Ewa, Kawaihae, and Lualualei may be classified under class 3. Though he made allowances for degree of dispersion in differentiating soils between class 1 and class 2, he did not do so to account for differences in degree of dispersion when remoulded at field capacity. As an example, the Honouliuli soil may be classified under a different subclass from the other soils which dispersed much less after being remoulded at field capacity. The same could be said about differences in degree of slaking of air dry aggregates in water, which could be significant in erosion studies.

When 1:5 soil-water suspensions were stirred with a glass rod

Table 2. Dispersion indices for remoulded (at field capacity) aggregates from surface soils

Soil type	Moisture content at which aggregates were remoulded	Dispersion index (%)
Molokai A_p	30.0%	0.0
Honouliuli A_p	30.2%	38.2
Ewa A_p	30.3%	8.9
Kawaihae A_1	26.0%	5.2
Lualualei A_1	29.8%	4.6
Lualualei A_1 (Kokohead)	34.5%	11.7

for 10 minutes, it was found that the Molokai soil, which had not been classified, became dispersed, and also because the Molokai soil was not known to contain carbonate or gypsum, it was thus classified under class 5 (refer to Table 3).

B. Effects of Prewetting on Breakdown of Surface Soil Aggregates

1. Wetting at 100 cm

It took between 5-7 days before the soil aggregates were completely equilibrated with the 100 cm suction or wetting. However, the aggregates were 90% equilibrated within two days or so. Table 4 shows the stability of the wetted aggregates when placed in a beaker containing 50 ml of water. The Molokai A_p, Honouliuli A_p, and Ewa A_p soils did not slake at all. The Kawaihae soil slaked to the 1st degree.

The relative stabilities of the soil aggregates at this treatment, in view of slaking behavior may be shown to follow this order: Molokai A_p = Honouliuli A_p = Ewa A_p > Kawaihae A > Lualualei A_1 > Lualualei A_1 from Kokohead. As mentioned earlier (in literature review section) slaking for wetted samples may be caused by shear stresses due to swelling or due to differential wetting or both. Since the above samples have already been equilibrated to the wetting suction, slaking could be more due to swelling stresses than differential wetting. The Molokai A_p and Ewa A_p consist mostly of nonexpanding type of mineralogy; thus they did not swell or slake. The Kawaihae soil, with a low clay content (33%), slaked due to its textural property which was sandy loam--slaking mainly being due to separation of sand particles more than repulsion of clay particles. Though the Honouliuli and Lualualei

Table 3. Stability of 1:5 soil-water suspension

Soil type	Dispersion index (%)
Molokai A_p	14
Honouliuli A_p	10
Ewa A_p	6
Kawaihae A_1	3
Lualualei A_1	5
Lualualei A_1 (Kokohead)	10

Table 4. Stability of aggregates prewetted at 100 cm suction

Soil type	Moisture content at 100 cm suction	Stability in distilled water**					
		0 hr		24 hr		48 hr	
		S	D	S	D	S	D
Molokai A_p	26.90%	0	0	0	0	0	0
Honouliuli A_p	24.27%	0	0	0	0	0	0
Ewa A_p	24.26%	0	0	0	0	0	0
Kawaihae A_1	30.32%	0	0	1	0	1	0
Lualualei A_1	27.21%	1	0	2	0	3	0
Lualualei A_1 (Kokohead)	35.86%	0	1	2	1	2	1

** 0 = No slaking (S) or dispersion (D)
5 = Complete slaking (S) or dispersion (D)

soils have almost similar mineralogical properties, the more stable property of the Honouliuli soil may be attributed to its lower clay content (61%) compared to those of the Lualualei (71%) and the Lualualei from Kokohead (78%). A similar reasoning may be applied to the higher stability of Lualualei soil compared to that sampled from Kokohead. The Kokohead samples also seemed to be wet more quickly than other samples, which caused more incipient failure.

2. Wetting at 50 cm Suction

At this suction, there were two samples for each soil type. One sample was prewetted at 100 cm and the other sample was freshly added at this suction. Although equilibrium was reached within 3 to 4 days, roughly 90% of wetting was reached after about one day. The stability of the aggregates wetted at this suction in distilled water and their moisture contents at equilibrium are given in Table 5. It was found again that regardless of whether or not the samples were prewetted at 100 cm, the Molokai A_p, Honouliuli A_p, and Ewa A_p soils were stable, i.e. did not slake nor disperse. Both samples of the Kawaihae A, prewetted at 100 cm and not previously prewetted, slaked to the 4th degree. The Lualualei A_1 prewetted previously at 100 cm slaked to the 2nd degree while samples of the Lualualei directly wetted at 50 cm suction slaked to the 3rd degree. The Lualualei from Kokohead samples swelled and dispersed to degree of 1 after 24 hours.

It is interesting to note that while other soils showed no differences in stability between prewetting treatments, the Lualualei A soils, wetted directly at 50 cm suction, were observed to be less stable than samples which were prewetted at 100 cm suction. This was probably

Table 5. Stability of aggregates at 50 cm suction

Soil Type	Suction at which aggregates were initially prewetted (cm)	Moisture content (%) of aggregates at 50 cm suction	Stability of aggregates at 50 cm suction in distilled water**					
			0 hr		24 hr		48 hr	
			S	D	S	D	S	D
M_1	100	30.08	0	0	0	0	0	0
M_1	nil	28.96	0	0	0	0	0	0
H_1	100	24.78	0	0	0	0	0	0
H_1	nil	25.76	0	0	0	0	0	0
E_1	100	24.27	0	0	0	0	0	0
E_1	nil	24.65	0	0	0	0	0	0
K_1	100	38.57	2	0	2	0	4	0
K_1	nil	37.92	2	0	2	0	4	0
L_1	100	29.63	1	0	1	0	2	0
L_1	nil	29.42	1	0	1	0	3	0
LK_1	100	44.96	0	0	*	1	*	1
LK_1	nil	37.12	0	0	*	1	*	1

*Aggregates swelled

** 0 = No slaking (S) or dispersion (D)
5 = Complete slaking (S) or dispersion (D)

due to the larger degree of incipient failure (Quirk, et al., 1962) which occurred more in samples directly wetted at 50 cm suction than in prewetted samples. The order of relative stabilities of soils at this suction is a little different, being Molokai A_p = Honouliuli A_p = Ewa A_p > Lualualei A_1 > Kawaihae A_1 > Lualualei A_1 from Kokohead. The Lualualei from Kokohead is assigned lower stability than Kawaihae since it dispersed in addition to slaking. The Kawaihae soil, however, behaved inconsistently perhaps due to its less developed field structure, i.e. it did not contain the coherent aggregates that the other soil types did.

3. Wetting at 30 cm Suction

When this suction was reached, there were three prewetting treatments for each soil type, one at 100 cm and then to 50 cm, the second at 50 cm, and the third was air dry sample directly wetted at 30 cm suction. The results are shown in Table 6. It was again demonstrated that the Molokai A_p, Honouliuli A_p, and Ewa A_p were stable regardless of prewetting treatments. Kawaihae A soil slaked to the 5th degree with the exception of the one that was wetted previously at 50 cm suction, which slaked to 3rd degree. This apparent inconsistency occurred because some fine roots held the particles together. There was change in the stability of the Lualualei soil at this suction, however. The Lualualei aggregates were stable at this suction, as opposed to their slaking behavior at two previous higher suctions. The Lualualei from Kokohead samples at this treatment behaved similarly as when wetted at 50 cm suction, i.e. they swelled and dispersed to 1st degree after 24 hours.

The change in behavior (stability) for the Lualualei

Table 6. Stability of aggregates at 30 cm suction

Soil Type	Suction at which aggregates were initially prewetted (cm)	Moisture content at 30 cm suction (%)	Stability of aggregates at 30 cm suction in distilled water***					
			0 hr		24 hr		48 hr	
			S	D	S	D	S	D
M_1	100-50	29.99	0	0	0	0	0	0
M_1	50	29.91	0	0	0	0	0	0
M_1	-	30.25	0	0	0	0	0	0
H_1	100-50	26.61	0	0	0	0	0	0
H_1	50	27.11	0	0	0	0	0	0
H_1	-	27.79	0	0	0	0	0	0
E_1	100-50	25.43	0	0	0	0	0	0
E_1	50	25.64	0	0	0	0	0	0
E_1	-	25.93	0	0	0	0	0	0
K_1	100-50	43.21	5	0	5	0	5	0
K_1	50	44.26	1*	0	1*	0	3*	0
K_1	-	47.91	5	0	5	0	5	0
L_1	100-50	32.17	0	0	0	0	0	0
L_1	50	31.69	0	0	0	0	0	0
L_1	-	33.69	0	0	0	0	0	0
LK_1	100-50	37.07	0	0	**	1	**	1
LK_1	50	46.85	0	0	**	1	**	1
LK_1	-	46.36	0	0	**	1	**	1

*Aggregates were held together by roots
**Swell
*** 0 = No slaking (S) or dispersion (D)
5 = Complete slaking (S) or dispersion (D)

samples at this suction may be due to the moisture content being the one at which there was no incipient failure when the sample were immersed in water. Other soils seemed to behave similarly to other treatments, and similar explanation may be applied for their results as well.

4. Wetting at 15 cm Suction

Results for the stability of the aggregates at this wetting suction are as shown in Table 7. All soils seemed to behave as at 50 cm suction. The Molokai A_p, Honouliuli A_p, Ewa A_p, and Lualualei soils again were stable regardless of prewetting treatments. The Kawaihae soils all slaked to the 4th degree with the exception of samples directly wetted at 15 cm suction, which slaked to the 5th degree. The Lualualei from Kokohead samples at this suction also behaved similarly to the previous treatments, i.e. swelled and dispersed to the 1st degree. After 24 hours, however, all other soil types at all prewetting treatments with the exception of Kawaihae soil showed a little dispersion coded as 1/2 degree. One probable reason is that the aggregates had been worked or accidentally remoulded while sampling for moisture content during the course of the experiment. The relative behavior of the soils were again to be interpreted the same way as in the previous wetting treatments.

C. Dispersion of Homoionic Soils Remoulded at Different Moisture Contents

The results for degree of dispersion of homoionic soils remoulded at different moisture contents and expressed as dispersion indices are given in Figures 8-20. As shown in Figures 8-20 and in

Table 7. Stability of aggregates at 15 cm suction

Soil Type	Suction at which aggregates were initially prewetted (cm)	Moisture content at 15 cm suction (%)	Stability of aggregates at 15 cm suction in distilled water**					
			0 hr		24 hr		48 hr	
			S	D	S	D	S	D
M_1	100-50-30	33.70	0	0	0	1/2	0	1/2
M_1^1	50-30	34.86	0	0	0	1/2	0	1/2*
M_1^1	30	35.50	0	0	0	1/2	0	1/2
M_1^1	-	38.07	0	0	0	1/2	0	1/2
H_1	100-50-30	29.74	0	0	0	1/2	0	1/2
H_1^1	50-30	31.59	0	0	0	1/2	0	1/2*
H_1^1	30	30.81	0	0	0	1/2	0	1/2
H_1^1	-	31.36	0	0	0	1/2	0	1/2
E_1	100-50-30	27.24	0	0	0	1/2	0	1/2
E_1^1	50-30	27.86	0	0	0	1/2	0	1/2*
E_1^1	30	27.44	0	0	0	1/2	0	1/2
E_1^1	-	28.52	0	0	0	1/2	0	1/2
K_1	100-50-30	47.12	3	0	3	0	4	0
K_1^1	50-30	36.32	4	0	4	0	4	0
K_1^1	30	51.07	3	0	3	0	4	0
K_1^1	-	56.79	5	0	5	0	5	0
L_1	100-50-30	35.94	0	1/2	0	1/2	0	1/2
L_1^1	50-30	36.32	0	1/2	0	1/2	0	1/2*
L_1^1	30	38.74	0	1/2	0	1/2	0	1/2
L_1^1	-	44.01	0	0	0	0	0	1/2
LK_1	100-50-30	50.49	0	0	≠	1	≠	1
LK_1^1	50-30	50.14	0	0	≠	1	≠	1
LK_1^1	30	51.49	0	0	≠	1	≠	1
LK_1^1	-	51.28	0	0	≠	1	≠	1

*Moulded during sampling

** 0 = No slaking (S) or dispersion (D)
5 = Complete slaking (S) or dispersion (D)

≠Swell

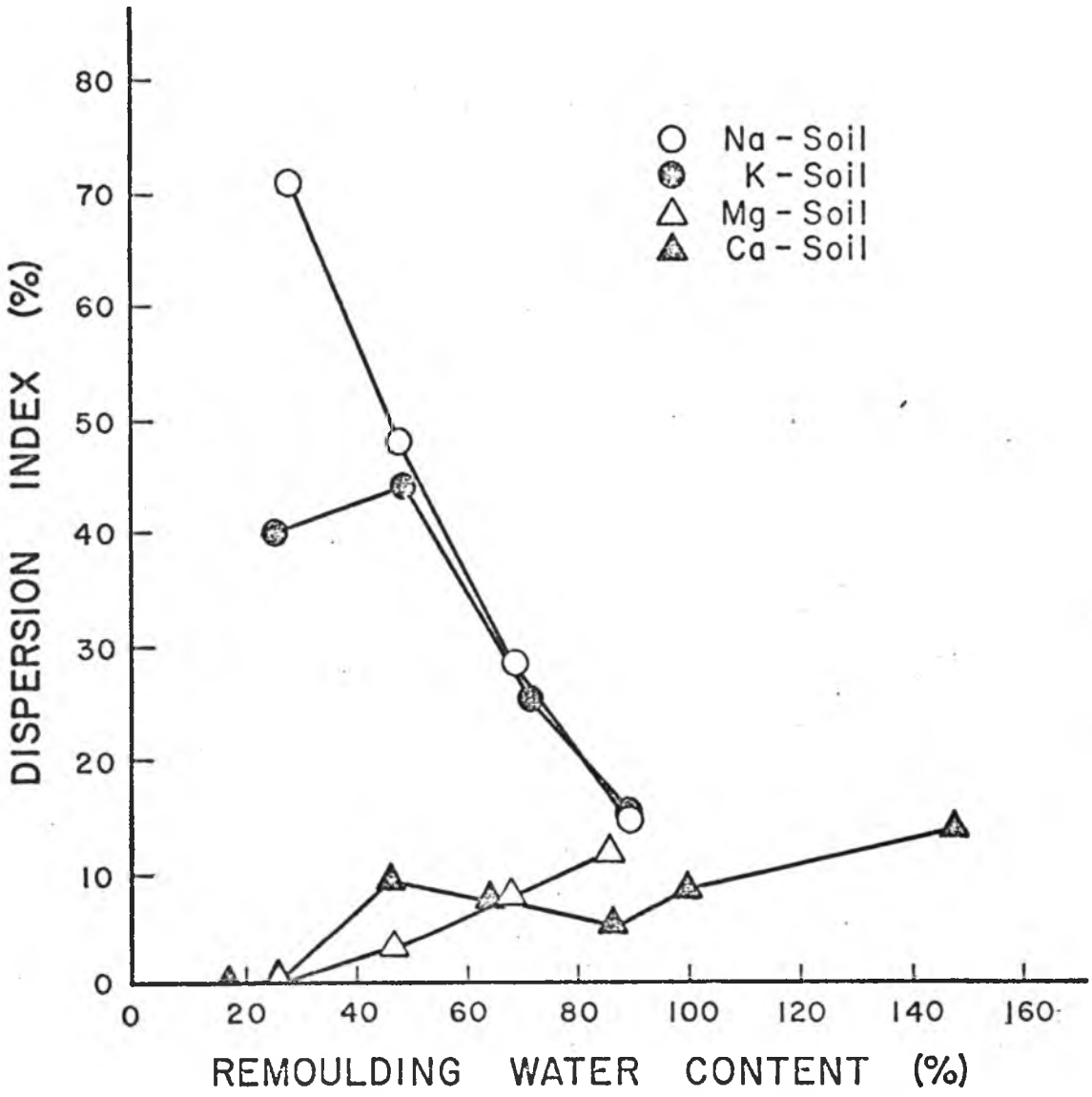

Figure 8. Relationship between water content at remoulding and the dispersion of Molokai A_p.

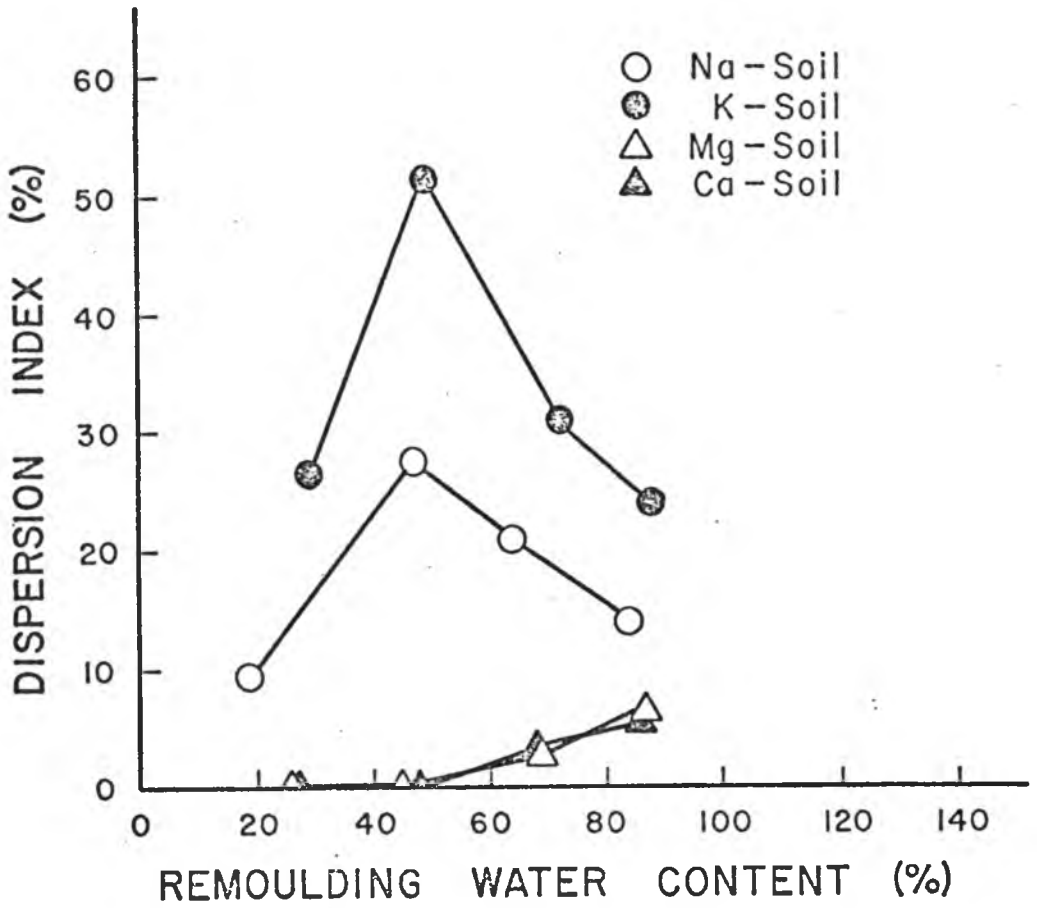

Figure 9. Relationship between water content at remoulding and the dispersion of Molokai B_2.

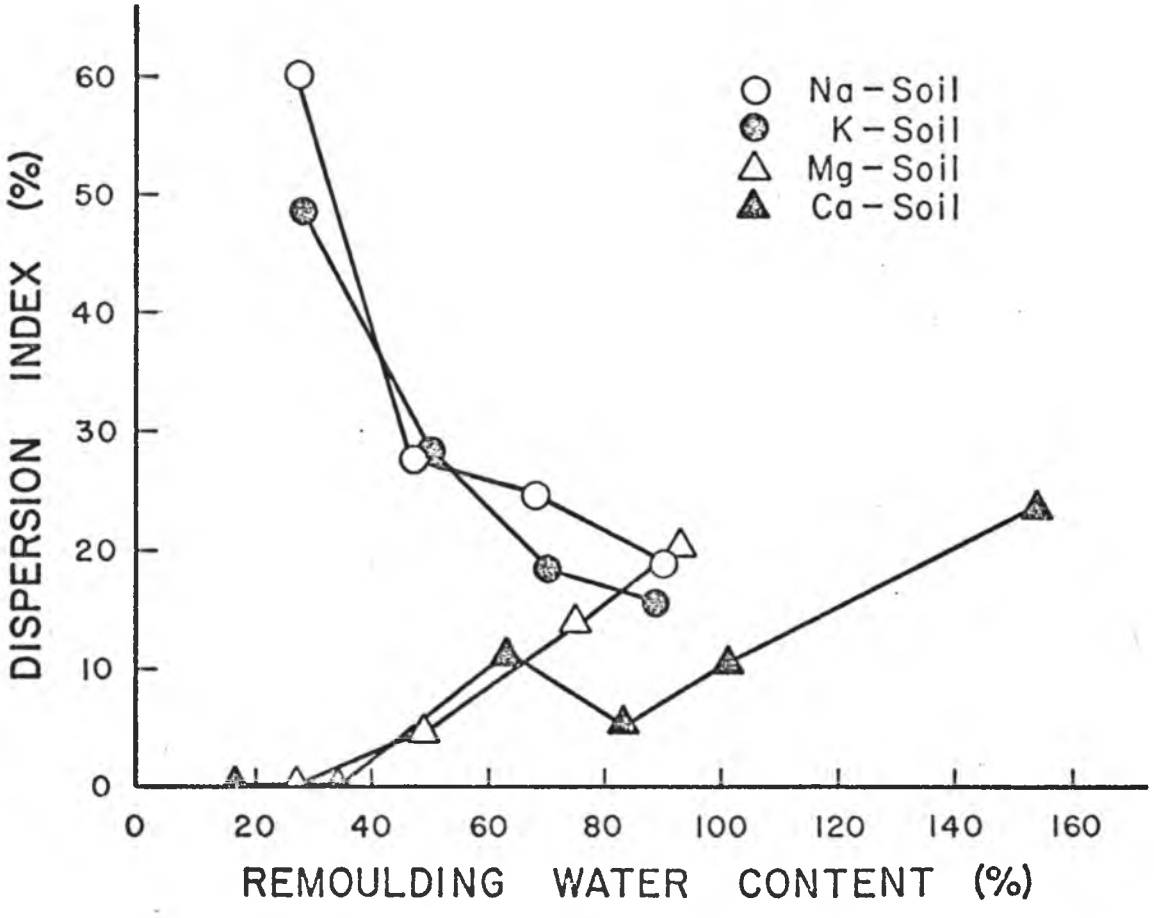

Figure 10. Relationship between water content at remoulding and the dispersion of Ewa A_p.

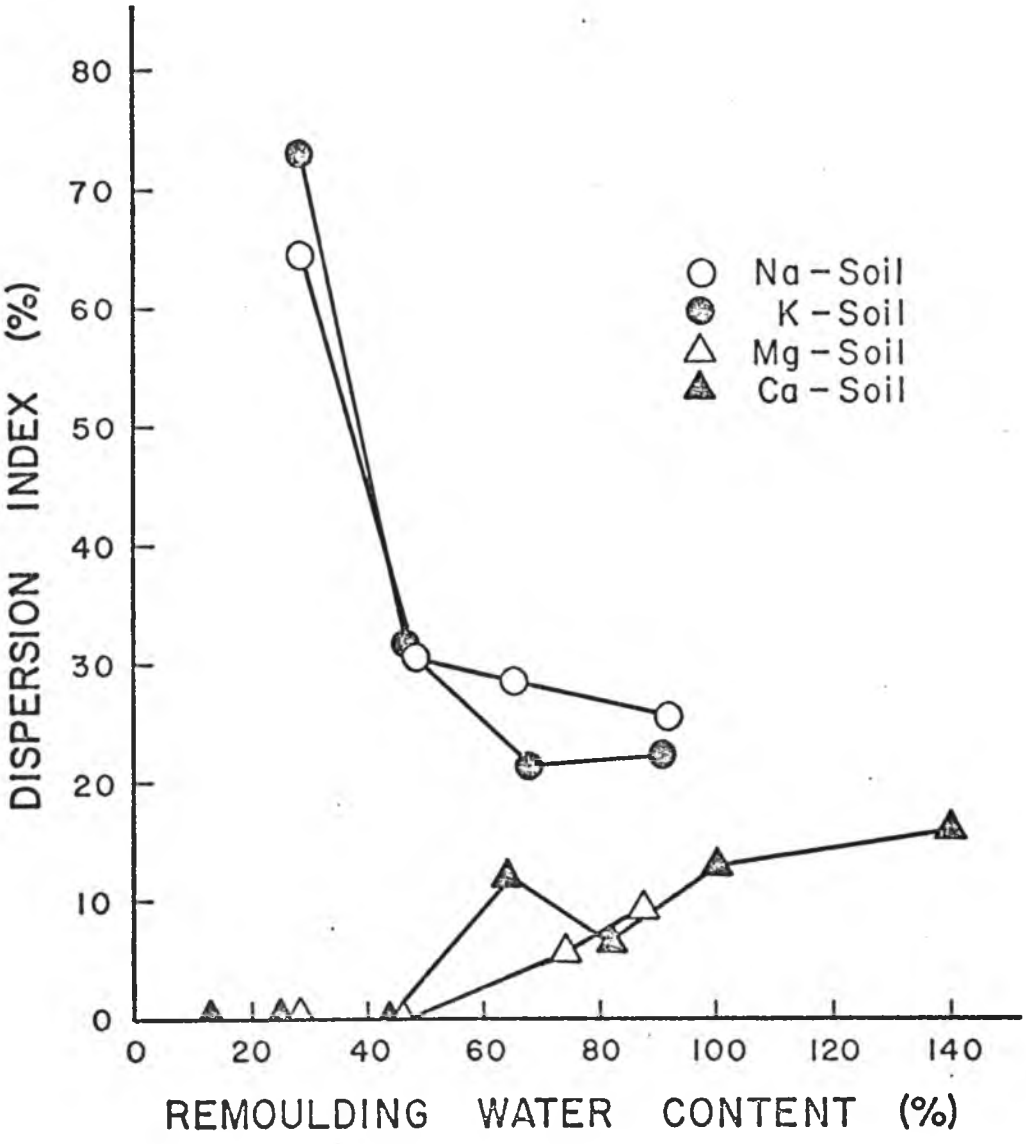

Figure 11. Relationship between water content at remoulding and the dispersion of Ewa B_2.

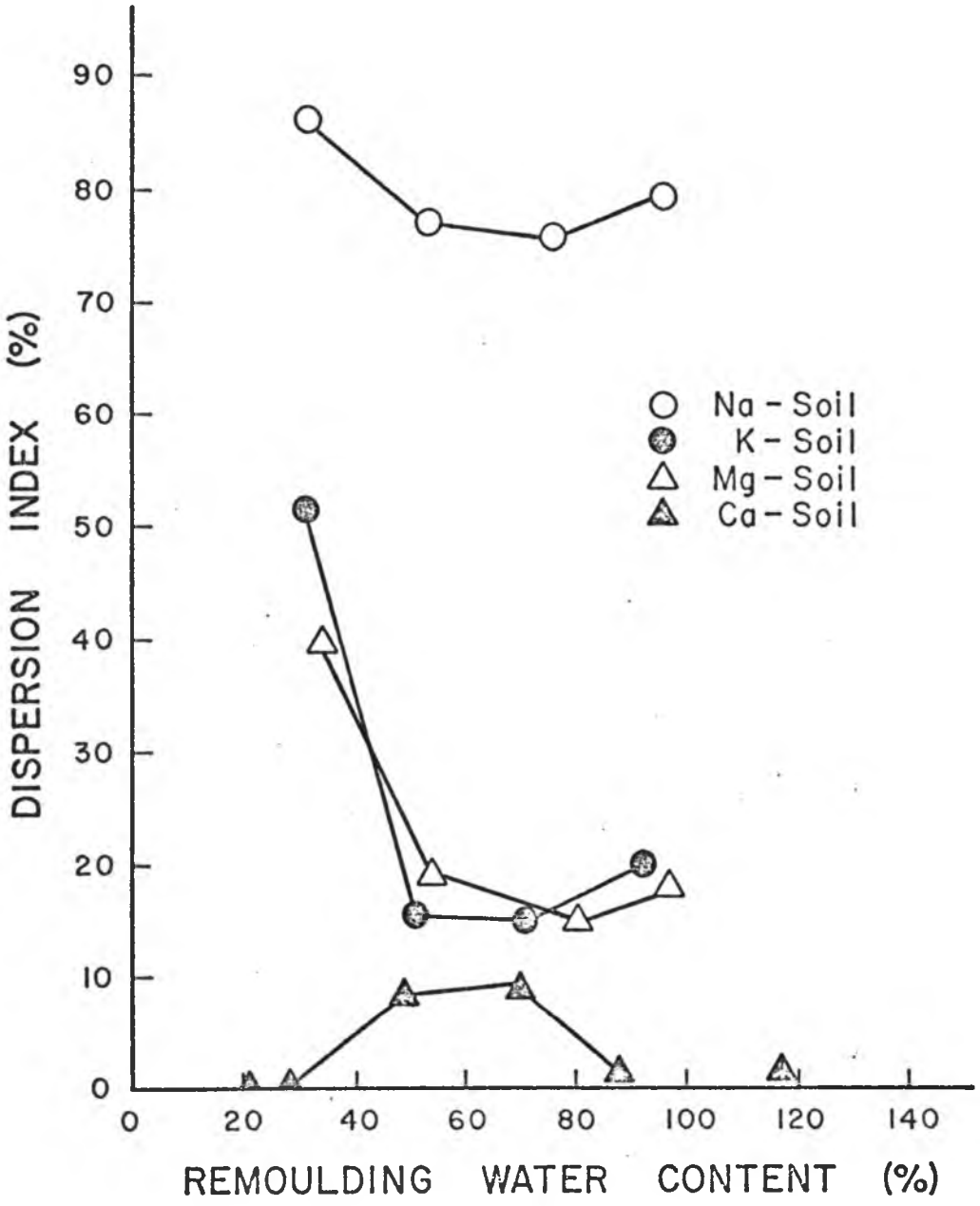

Figure 12. Relationship between water content at remoulding and the dispersion of Honouliuli A_p.

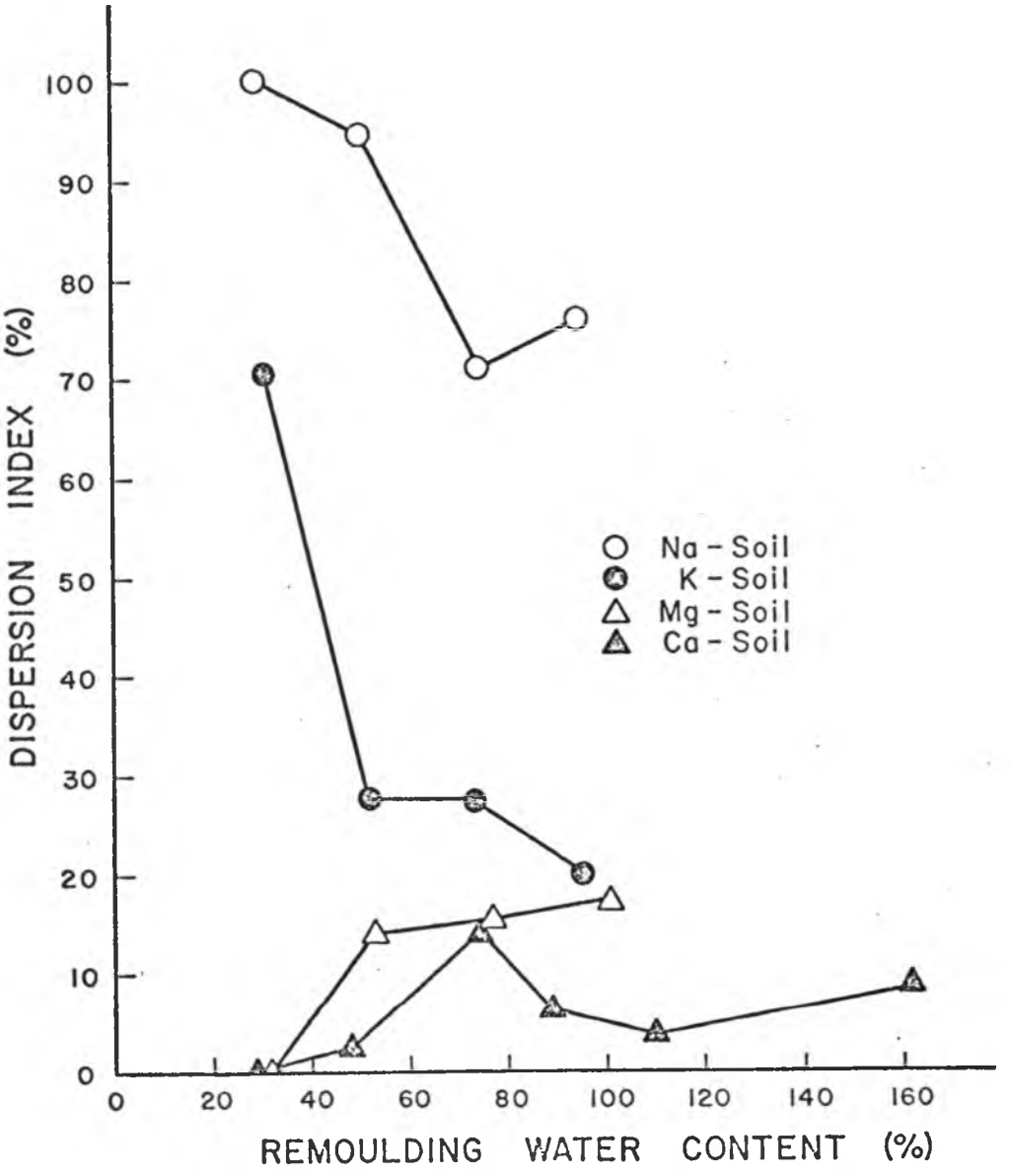

Figure 13. Relationship between water content at remoulding and the dispersion of Honouliuli B_2.

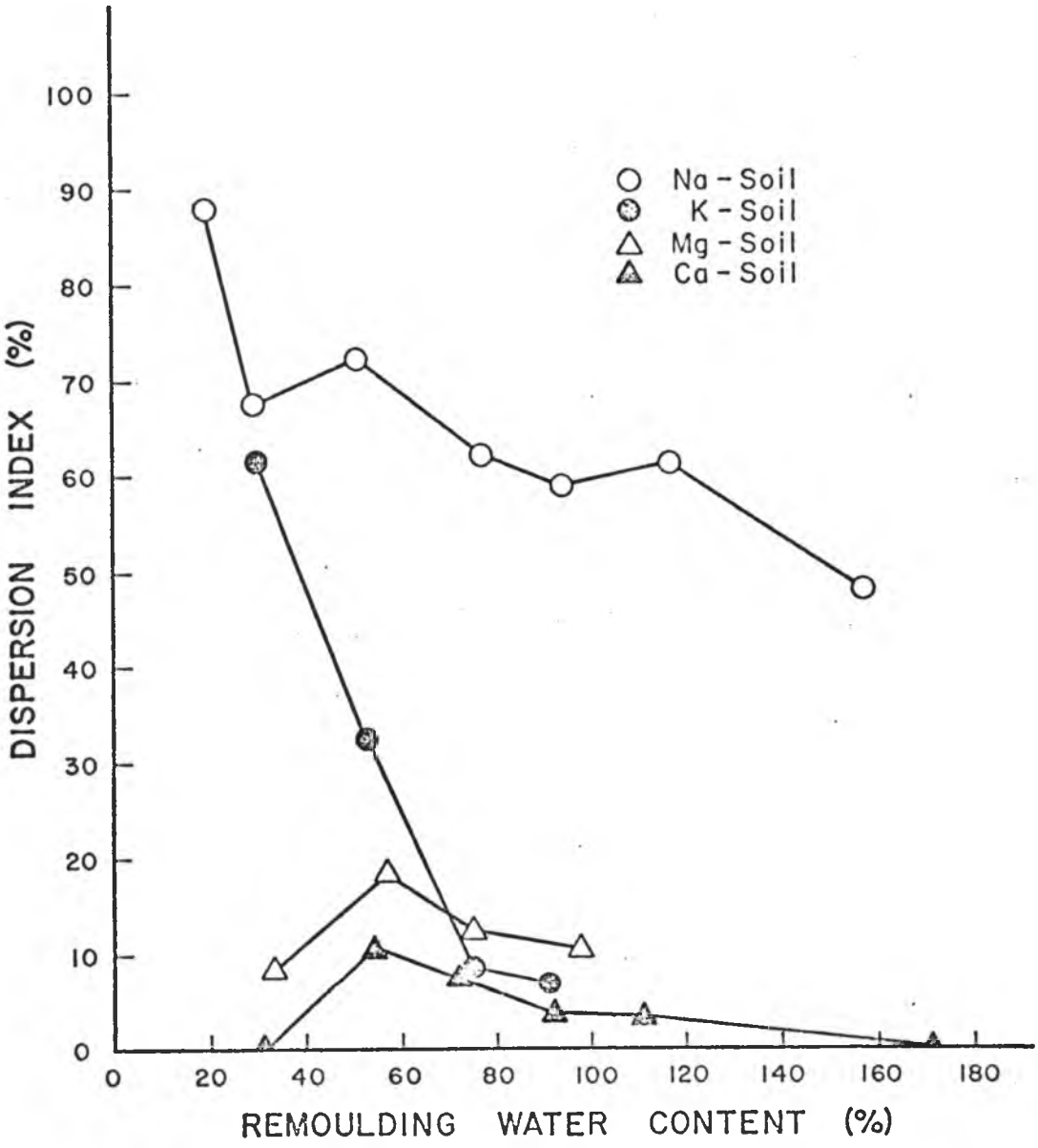

Figure 14. Relationship between water content at remoulding and the dispersion of Lualualei A_{11}.

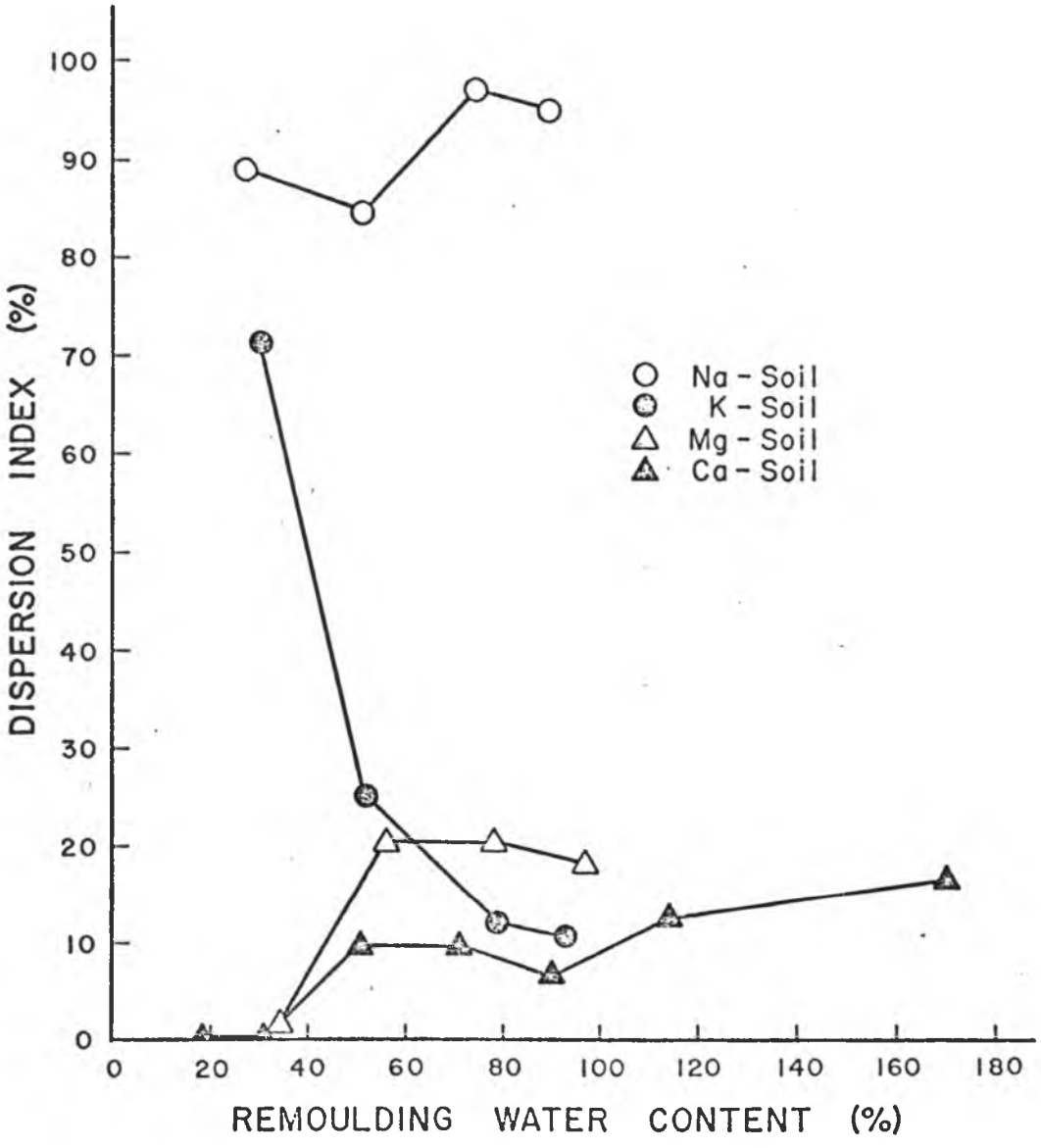

Figure 15. Relationship between water content at remoulding and the dispersion of Lualualei A_{12}.

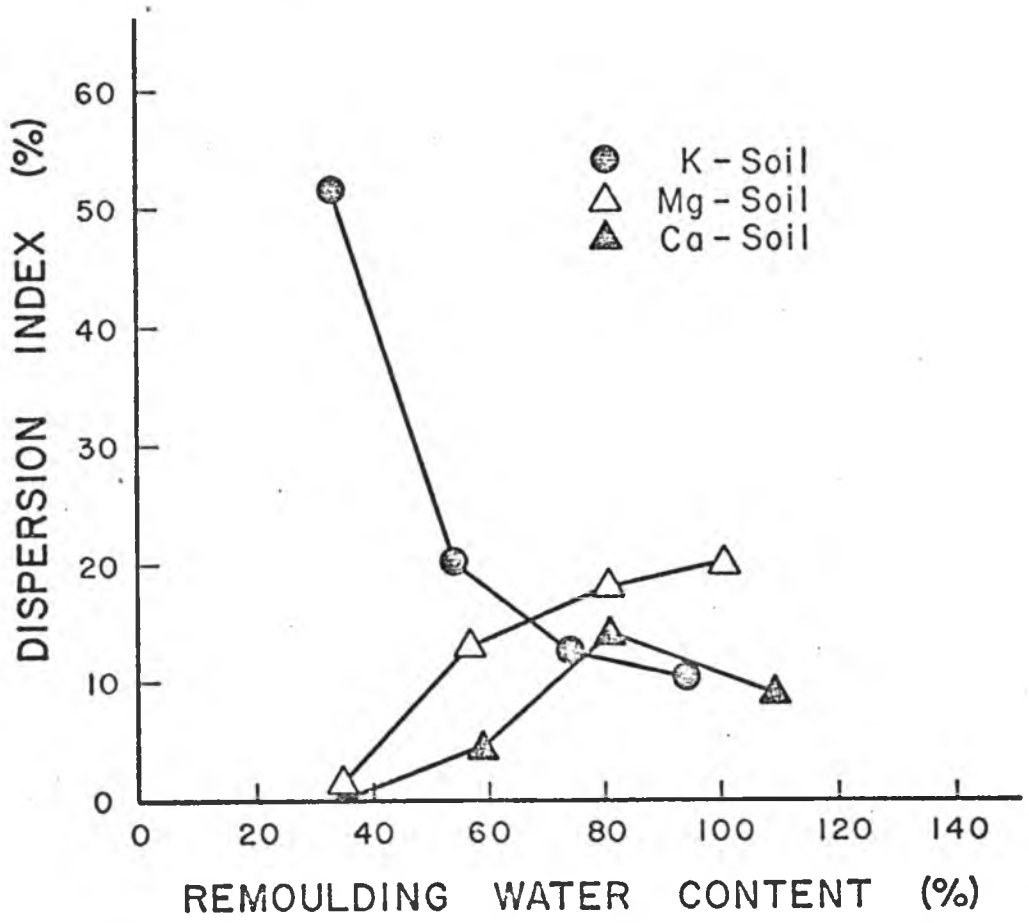

Figure 16. Relationship between water content at remoulding and the dispersion of Lualualei A_c.

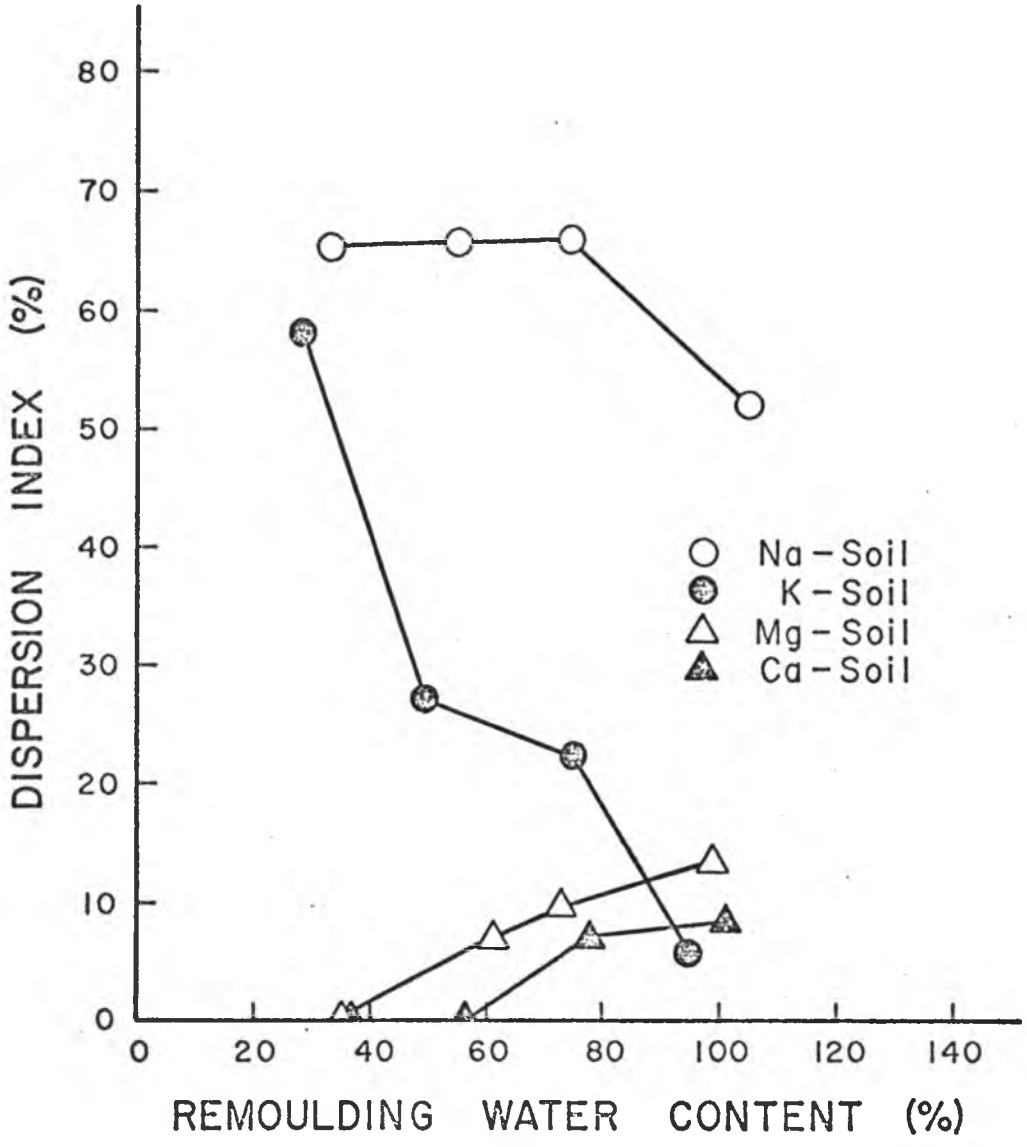

Figure 17. Relationship between water content at remoulding and the dispersion of Lualualei (Kokohead) A_1.

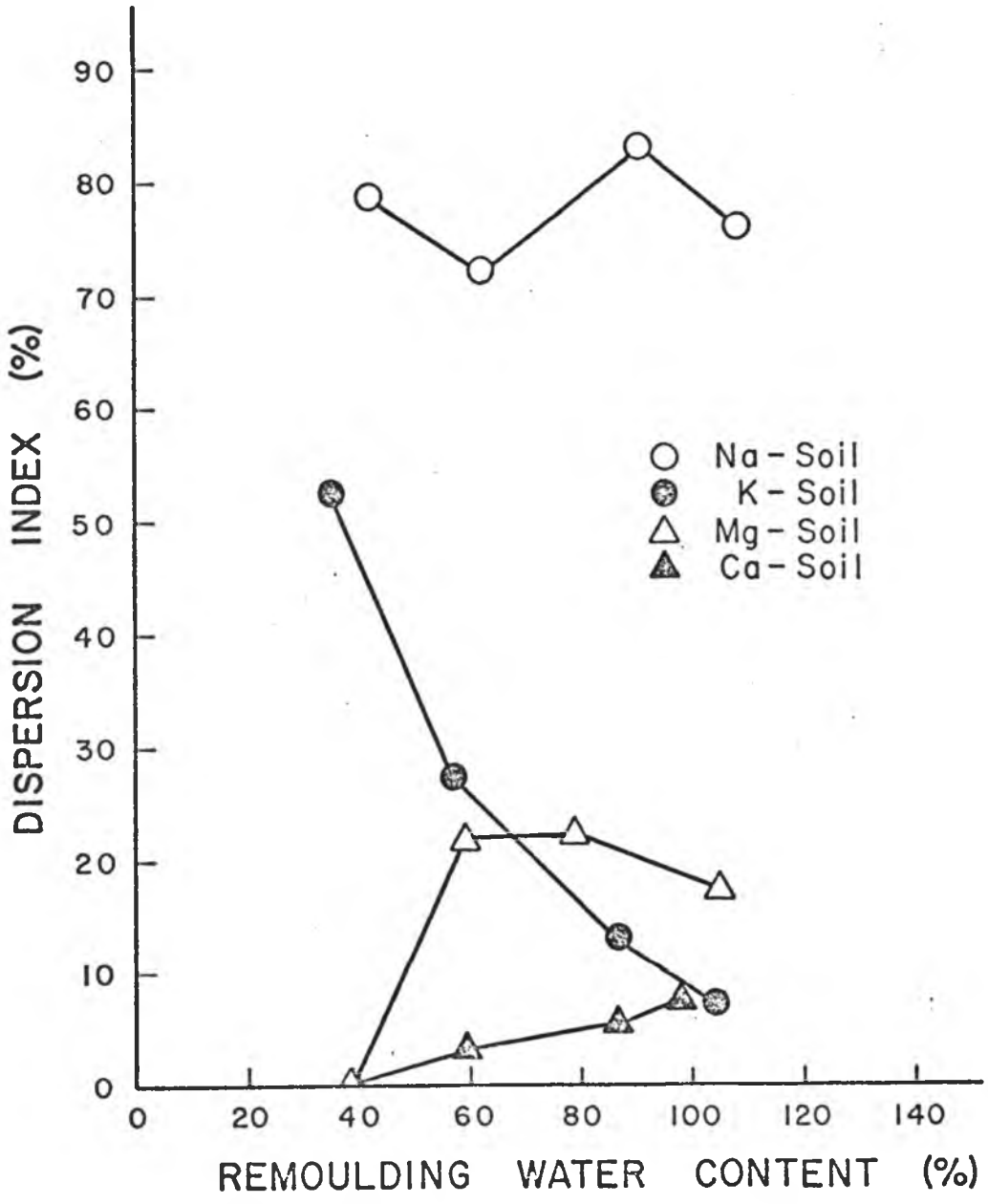

Figure 18. Relationship between water content at remoulding and the dispersion of Lualualei (Kokohead) A_{11}.

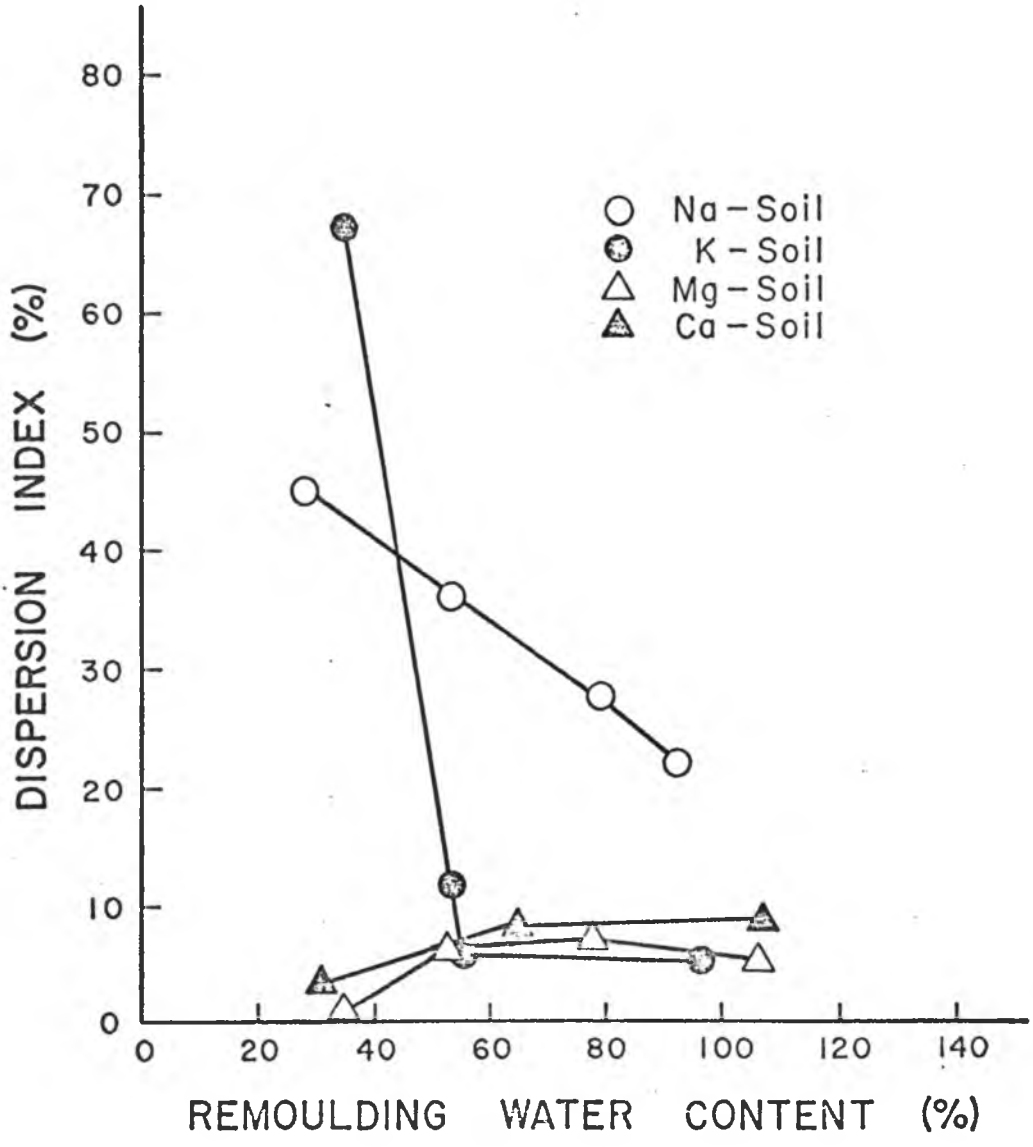

Figure 19. Relationship between water content at remoulding and the dispersion of Kawaihae A_1.

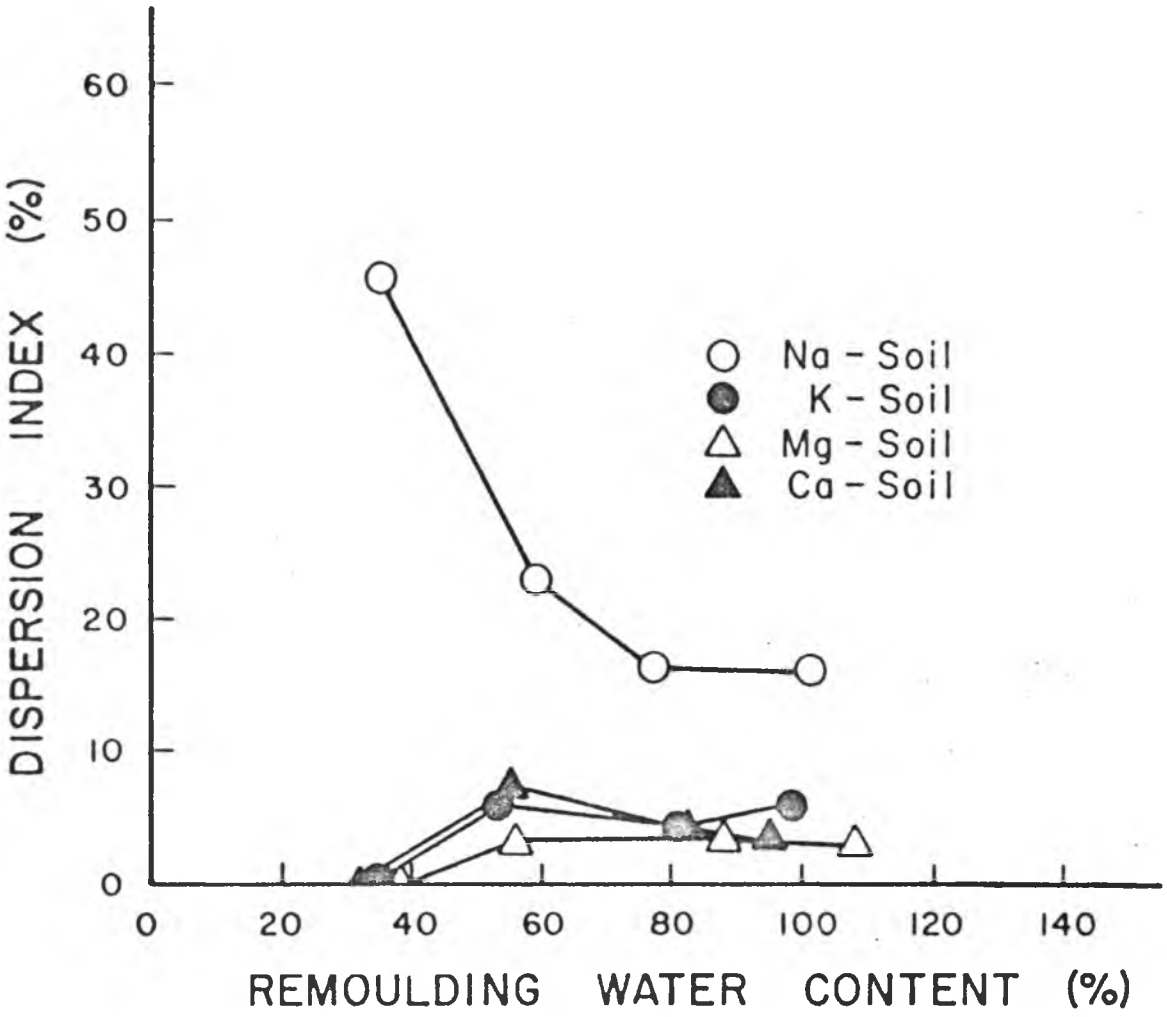

Figure 20. Relationship between water content at remoulding and the dispersion of Kawaihae B_2.

Appendices E, F, G, and H, the dispersion generally decreased when water contents for remoulding of monovalent-saturated soils were increased. For divalent-saturated soils, however, after a water content for minimum dispersion has been reached, the dispersion again increased with increasing remoulding water content. Water contents for dispersion of divalent-saturated soils were higher than monovalent-saturated samples.

1. Molokai Soils

a. Effects of Cations

Comparison of results presented in Figures 8 and 9 show that monovalent saturated samples of both horizons of the Molokai soil dispersed more than the divalent saturated samples with dispersion index for monovalent-saturated soils ranging from 19-71% and for divalent forms ranging from 0-12% at the range of remoulding water content employed. The water content necessary to produce initial dispersion was also higher for divalent than for monovalent cations. Between cations of same valency, water content for K soil was higher than for Na, and for Mg higher than for Ca soils. It was noted, however, that while for surface soil the dispersion of Na and K samples was almost the same, Na-samples of subsurface soil were dispersed to a lower degree than K-samples. Dispersion of Mg and Ca samples was similar.

b. Effect of Soil Horizon

The Na-samples of the surface horizon (A_p) were more dispersed than the subsurface horizon, with the dispersion indices of surface soil ranging from 15-71% and those of subsurface from 9-27%. The K-samples of both horizons showed almost similar dispersion. The dispersion of all other cation-saturated samples of surface soils were

lower than those of respective cation-saturated samples of subsurface soils showing that the latter were less easily dispersed.

2. Ewa Soils

Results for this soil are shown in Figures 10 and 11.

a. Effects of Cations

The dispersion of monovalent-saturated soils was consistently higher than for divalent-saturated soils, the range of dispersion indices for monovalent soils being 15-73% while those of divalent being 0-21%. The dispersion index decreased for monovalent samples and increased for divalent samples as the moisture content at remoulding was increased. The moisture content for maximum dispersion was less for monovalent cations than for divalent cations. The degree of dispersion between soils saturated with cations of the same valency was similar at almost all moisture content at remoulding.

b. Effect of Soil Horizons

There was no pronounced difference in dispersion of the two horizons of Ewa soil at all moisture contents; but the surface samples generally dispersed to a higher degree than subsurface samples. The K-saturated sample was an exception. At 27% remoulding moisture content, K-samples of the subsurface horizon were found to disperse more than the surface samples, i.e. the dispersion indices were 73% and 48%, respectively. All monovalent samples of both horizons dispersed at the lowest moisture content applied in the experiment (about 27%), but for divalent samples, the Mg-saturated samples of surface horizon dispersed at a lower moisture content than those of horizon B, while Ca-saturated samples of both horizons seemed to behave almost similarly.

3. Honouliuli Soil

Figures 12 and 13 give the results for Honouliuli soil.

a. Effect of Cations

Comparing the effects of cations, it was again shown that the dispersions of monovalent-saturated samples were greater than those of divalent samples for both horizons. Between cations of equal valency, Na-saturated samples were more dispersed than K-saturated samples and Mg-saturated samples were more dispersed than Ca-saturated samples. The previously noted trend that monovalent-saturated samples showed decreased dispersion and divalent soils increased dispersion with increasing remoulding moisture content was again confirmed. One exception was the Mg-saturated samples of A_p horizon which behaved as did K- or Na-samples initially showing decreases in dispersion with increasing moisture content, but indicating a little increase in dispersion after moisture content at remoulding exceeded 80%. The Ca-saturated samples, however, exhibited decreased dispersion at moisture content higher than 80%. The monovalent samples dispersed at lower moisture content than the divalent samples.

b. Effect of Soil Horizon

Generally it was found that at the same moisture content or cation saturation, the subsurface samples were more dispersed than surface samples, in contrast to what was observed in the other soils.

4. Lualualei Soil

Results for this soil are as shown in Figures 14, 15 and 16.

a. Effect of Cations

It was again demonstrated that the monovalent saturated samples showed greater dispersion than the divalent saturated samples with Na-samples dispersing more than K-samples and Mg-samples more than Ca. The degree of dispersion of monovalent samples of all three horizons still decreased with increasing moisture content at remoulding, except for Na-samples of the top horizon which fluctuated as moisture content at remoulding decreased. (Experiments on the Na-Lualualei A_c were not done because there was a shortage of samples.) The monovalent samples of Lualualei soils also dispersed at lower moisture content than did the divalent samples. At remoulding moisture content higher than 70%, the dispersion index of K-soils was lower than that of Mg but higher than or almost the same as that of Ca soils.

b. Effect of Soil Horizon

All three horizons seemed to disperse to about the same degree regardless of treatment, with the exception of horizon A_{11} treated with Na ions, which dispersed considerably more than horizon A_1. Furthermore, the general trend of decreasing in degree of dispersion with increased moisture content at remoulding was not demonstrated by this A_{11} horizon. Instead, its dispersion increased and decreased inconsistently as the moisture content at remoulding increased.

5. Lualualei from Kokohead

Results are as shown in Figures 17 and 18.

a. Effect of Cations

As for the other soils, the dispersion of monovalent-saturated soils for this soil was again higher than the divalent-saturated samples, with Na-samples dispersing more than K-samples, and

Mg-samples more than Ca-samples. The decrease in dispersion of monovalent samples and increase in dispersion of divalent samples with increase in moisture content at remoulding was again demonstrated. However, the Na-samples behaved a little differently for the surface horizon, as the moisture content at remoulding increased the dispersion index at first increased, remained constant, and then began to decrease. For the B_2 horizon, the dispersion index fluctuated, behaving like that of Lualualei A_{11} mentioned previously. The moisture contents for dispersion for divalent samples were also higher than those for monovalent samples, as was found in the other soils.

b. Effect of Soil Horizon

The dispersion of the subsurface horizon seemed to be higher than the surface horizon, and the Na and Mg samples of subsurface horizons showed greater dispersion than the surface horizon.

6. Kawaihae Soil

Figures 19 and 20 show the results for the Kawaihae soil.

a. Effects of Cations

It can be seen again that the dispersion indices of monovalent-saturated samples were greater than those of divalent-saturated samples. However, at 35% moisture content, the K-saturated surface soil dispersed to almost 70%, while at other moisture contents, K-samples seemed to behave as did the divalent saturated samples. The trends for the other samples still were the same with the Na-samples showing decreased dispersion with increasing moisture content while the divalent-samples showed increased dispersion up to a certain extent and then remained more or less constant. As noted for other cases the

moisture content for dispersion for monovalent samples was smaller than for divalent samples.

b. Effect of Soil Horizon

K-saturated B_2 samples behaved differently from surface horizon samples but similarly to divalent-saturated samples of both horizons. However, it was noted that the different behavior of K-saturated samples was only at the lowest water content used for remoulding. At higher water content than this, the two horizons began to disperse almost similarly, and the degree of dispersion was similar to those of Mg and Ca samples. The dispersion of Na-saturated surface samples was a little higher than that of subsurface samples. Otherwise Mg, Ca, and K samples of the two horizons showed similar dispersion behavior.

D. Discussion on Dispersion of Homoionic Soils Remoulded at Different Moisture Contents

1. Effect of Cations

The effect of cation saturation on the dispersion of soils seemed to be significant for all soil types. The effect in decreasing order of dispersion of soils by cations were Na > K > Mg > Ca. The effects were in agreement with the Schulze-Hardy rule which states that the relative flocculating powers of cations are determined by their valencies. This had been successfully explained by the theory of stability of lyophobic sols (Verwey and Overbeek, 1948). There was however an exception in the case of the Kawaihae, a kaolinitic soil, in which K effects were similar to those of Ca and Mg. Similar results

regarding the behavior of K-saturated Lualualei soil was observed by Ahmed (1969) and El-Swaify, et al. (1970), in which the dispersion of K-saturated Lualualei soil was found to be lowest compared to those of Na-, Ca-, and Mg-saturated soils with the Na-saturated soil being the highest. This different behavior of K-saturated soil was attributed to the K-ions being specifically adsorbed in the hexagonal cavities of the tetrahedral layers of the clay, thus behaving differently from what is predicted by the Schulze-Hardy rule. However, K-saturation in the experiment did not produce reduction in dispersion of the soil, in contrast to what was found by the above cited authors. It can only be assumed that there was no specific adsorption of K-ions by the Lualualei soil but only by the Kawaihae soil in this study. In addition to the above, it was found that the degree of dispersion for Molokai soil was dependent on cation saturation--not in agreement with Ahmed (1969) who found that dispersion of Molokai soil did not depend on the type of cation. This discrepancy may have been due to differences in the method of homoionic soil preparation and assessing the degree of dispersion in these two studies. Ahmed (1969), on one hand, prepared the homoionic soils by "batch" method, while in this experiment, the homoionic soils were prepared by leaching the soils with appropriate electrolytes and washing the excess salt with distilled water or methanol after equilibrium had been reached. The soils might not have been fully saturated with the respective cations by the former method as compared to the latter. In assessing the degree of dispersion, Ahmed (1969) used mechanical analysis while in this experiment the dispersion was assisted through remoulding, and the amount of clay going into suspension was

measured by turbidity.

Another exception to the dispersion behavior not in accord with the Schulze-Hardy rule is that of the Mg-saturated Honouliuli A_p soil, which had dispersion characteristics similar to those of monovalent-saturated soils. Similar finding for some Mg-saturated soil was mentioned by Ahmed (1969) and was attributed to the formation of univalent Mg ion complexes such as $(MgOH)^{+}$.

Looking through the base saturation values of the two horizons of the soil series studied (Kanehiro, et al., 1956, and Hawaii Soil Data Bank, 1975, unpublished), showed that with the exception of Honouliuli (both horizons of which have 100% base saturation), all the surface horizons of the other soils studied had higher base saturation values than the subsurface horizons. This shows that the subsurface horizons had higher amounts of exchange acidity on the exchange complexes than the surface horizon. It would have been difficult for the Al^{3+}, $Al(OH)^{+2}$, or $Al(OH)_2^{+1}$ to be replaced by Ca, Mg, K, or Na during the leaching for preparation of homoionic soils. The presence of Al^{+3} and other forms of exchange acidity, in addition to a lower amount of organic matter in the subsurface soil, may have reduced the amount of dispersion of clay in these soils.

The distances between clay plates are determined by their moisture content, the higher the moisture content, the greater is the distance. The difference between the moisture content necessary to produce dispersion in divalent and monovalent clays (higher for divalent than for monovalent) may be explained by the differences in effective distances between the clay particles before repulsion among them was produced.

2. Effect of Soil Horizon

Results showed that for most soils, the surface horizons were more dispersed than the subsurface when not equal, but the differences in dispersion varied according to soil types. The only soil whose subsurface horizon was observed to disperse more than the surface horizon was the Honouliuli soil.

Emerson (1968) discussed two conditions in which clay crystals may be dispersed from soil aggregates. First, when the average spacing between the clay crystals forming the soil aggregates have been sufficiently large that when immersed in water, the aggregates dispersed spontaneously. This initial average spacing increased with increasing moisture content and remoulding of the aggregates. If dispersion depends only on the spacing between the crystals, once a uniform paste has been formed, further remoulding has no effect. If by further remoulding, additional bonds are broken, for example organic matter bonds linking the clay crystals together, the susceptibility of the clay to dispersion will be increased. This was the second condition discussed by Emerson (1968).

The difference in degree of dispersion between the surface and subsurface horizons of soils may be attributed to the greater abundance of organic matter in surface soil than in subsurface soil. The presence of organic matter enabled the remoulded aggregates to be dispersed more easily. Similar results were found by Emerson (1968) who showed that oxidized soils dispersed at a higher water content than did natural soils.

3. Effect of Soil Types

Examination of Figures 8-20 or Appendixes E to H shows that the dispersion of the Vertisols (Honouliuli, Lualualei, and Lualualei from Kokohead soils) was higher than the Molokai, Ewa, or Kawaihae soils, especially for the Na-saturated soils. While the Honouliuli soil consisted mainly of expanding 1:1 clays and some 2:1 clays, and the Lualualei soils consisted mainly of 2:1 clays, the Molokai, Ewa, and Kawaihae soils contained, in different proportions, kaolinite, amorphous materials, gibbsite, and hematite. The presence of higher cation exchange capacity in the first group of soils than in the second group, may have contributed more charges for interaction between clay particles, thus inducing more dispersion, which was manifested in the Na-saturated soils. Though the Kawaihae soil had a cation exchange capacity comparable to those soils of the first group, it also had less base saturation (69-77%) than the Honouliuli or Lualualei soils (which had 100% and 97-100%, respectively). The presence of Al^{3+}, its polymers, or H^{+} in the Kawaihae soil and of amorphous materials, gibbsite, and hematite in the Molokai, Kawaihae, and Ewa soils appear to have influenced decreased dispersion in these soils relative to the Vertisols.

E. Dispersion of Natural Aggregates at 50 cm Suction in 0.001M and 0.1M Sodium Pyrophosphate Solution

The results for this experiment are as shown in Table 8. When the samples wetted at 50 cm suction were immersed in 50 ml of 0.001M sodium pyrophosphate solution overnight, the degree of dispersion of the

Table 8. Dispersion of natural aggregates at 50 cm suction and immersed in 0.001M and 0.1M sodium pyrophosphate solution

Soil type	D.I. (%)		Moisture content at 50 cm suction (%)
	.001M	0.1M	
Molokai A_p	2.51	3.69	28.52
Ewa A_p	6.02	14.57	24.99
Honouliuli A_p	34.61	78.70	24.81
Lualualei A_1	28.22	48.45	29.07
Lualualei A_1 (Kokohead)	54.93	72.19	43.67
Kawaihae A_1	0	0	39.76

soils (as dispersion index (%)) decreased in the following order: Lualualei from Kokohead > Honouliuli A_p > Lualualei A_p > Ewa A_p > Molokai A_p > Kawaihae, with the Kawaihae soil not dispersing at all but remaining coherent. However, when the samples were first immersed in 0.1M sodium pyrophosphate overnight, the solution decanted and 50 ml of 0.001M sodium pyrophosphate solution slowly added, the order of the soils with decreasing dispersion index was changed to: Honouliuli A_p > Lualualei A_1 from Kokohead > Lualualei A_1 > Ewa A_p > Molokai A_p > Kawaihae A_1, with the Kawaihae soil again showing no dispersion at all. There was also a marked increase in dispersion in the Honouliuli, Lualualei, Lualualei from Kokohead and to some extent the Ewa soil.

Immersing the soil aggregates in the sodium pyrophosphate solution increased the dispersion, except for Kawaihae, over immersion in distilled water. In addition, equilibrating the soil aggregates with 0.1M sodium pyrophosphate solution before immersing in 0.001M solution had further increased the dispersion of the soil; again the Kawaihae soil was an exception. This increase in dispersion may have been caused by either increased adsorption of Na as exchangeable ion, or an increased adsorption of negative pyrophosphate ion. Adsorption of pyrophosphate ion caused an increase of negative charges on the soil clays, or had a neutralizing effect on the positively charged hydroxides and the exchangeable Al. The increase in dispersion was very significant in the Honouliuli A_p, and the two Lualualei soil types. These soils consist primarily of expanding 1:1 and 2:1 clays, respectively, with the clay surfaces being mostly negatively charged under normal pH conditions. The increase in negative charge due to adsorption of

pyrophosphate ions has increased the repulsive forces between the clay particles. The further increase in dispersion of soils after treatment with 0.1M sodium pyrophosphate solution may be attributed to both increased adsorption of sodium on the exchangeable base sites as well as of pyrophosphate ions on the exchangeable Al. The increase in dispersion in the Ewa and Molokai soils, which was less than for the other three soils, may be attributed to the increase in exchangeable Na on the clay surfaces. The adsorption of pyrophosphate ions may not be sufficient to induce dispersion, especially in the presence of the oxides and hydroxides of Fe and Al. The apparent lack of response from the Kawaihae soil to pyrophosphate treatment was probably due to insufficient adsorption of pyrophosphate to develop negative charge in magnitude large enough to produce repulsion as was discussed for the Ewa A_p and Molokai A_p soils. In addition the clay content for the Kawaihae A_1 soil was very low (33%), and the base saturation of the exchangeable complex was also low, making it less possible for sodium to be adsorbed.

II. Colloidal Stability Studies

A. Flocculation Series Test

The flocculation values of the various electrolytes were taken as the concentration at which 25% of the clay still remained in suspension. These values were interpolated from the curves of the flocculation series tests in which the turbidity readings were plotted against electrolyte concentration. As an illustration, Figure 21 shows one of the flocculation series curves for Na-Honouliuli A_p soil in $NaHCO_3$ solution in which the flocculation value is 0.25 N.

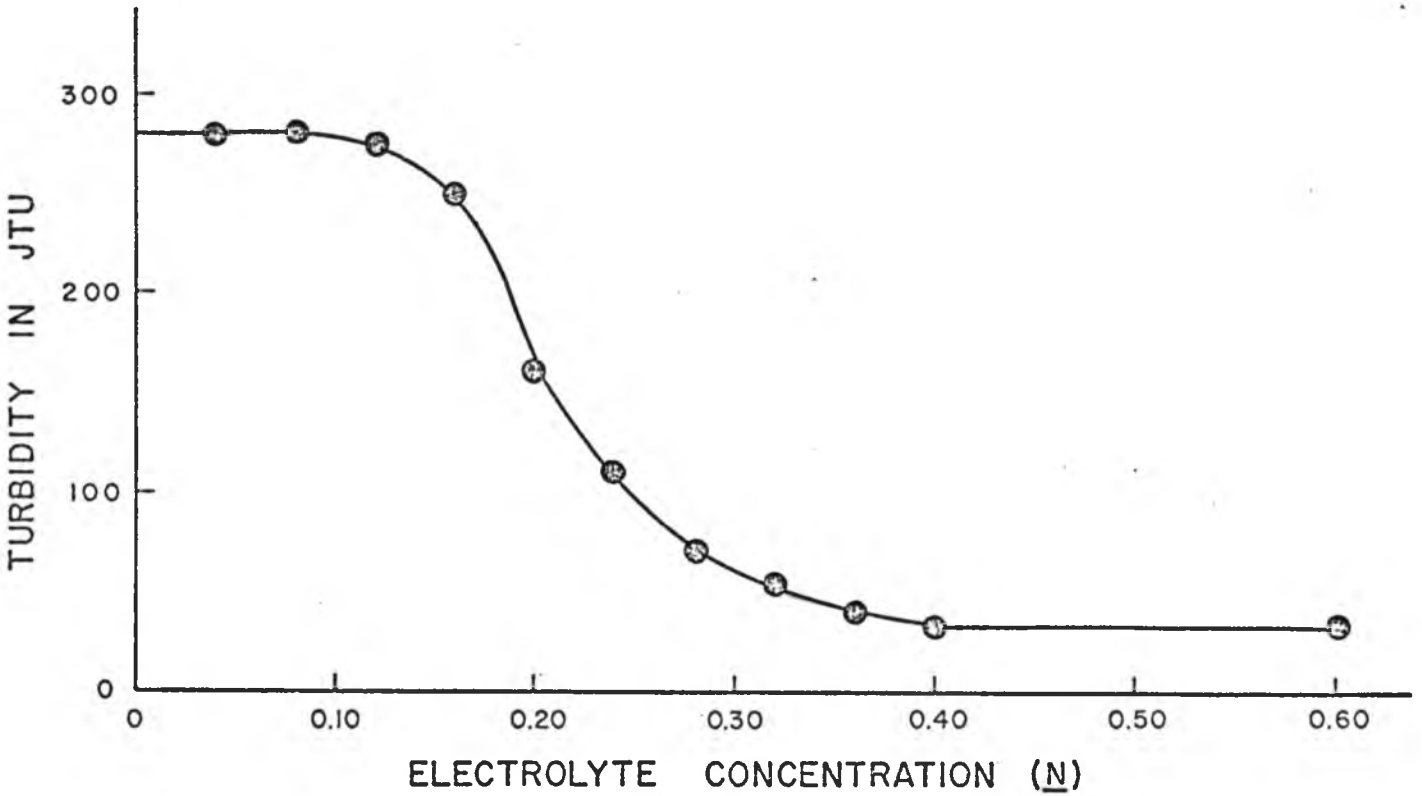

Figure 21. Flocculation series curve for Na-Honouliuli A_p in $NaHCO_3$ solution.

Tables 9-12 show the results of the flocculation values as concentration of the electrolyte in "normality" for the Na-, K-, Mg- and Ca-soils respectively, with chloride, sulphate and carbonate/ bicarbonate as the co-ions (pairing anions). The pH ranges of each flocculation series are also given.

1. Effect of Cations

From Table 9, it may be generalized that, for all soils, flocculation values for Cl^-, $SO_4^=$, and HCO_3^- of sodium fall in the range of 0.001 - 0.075 N, 0.005 - 0.196 N, and 0.070 - 0.300 N, respectively. Table 10 is for K-salts and the flocculation values are 0.004 - 0.066 N, 0.004 - 0.075 N and 0.032 - 0.120 N for Cl^-, $SO_4^=$, and HCO_3^- systems, respectively. The ranges for Mg-salts, as given in Table 11, were from 0.0001 - 0.0020 N, 0.0001 - 0.0020 N for chloride and sulphate respectively, and there was no flocculation produced at the range of concentration of magnesium carbonate used in the experiment, which was between 1.18×10^{-4} - 7.11×10^{-4} N, was quite low due to low solubility of the salt. For Ca-salts, the ranges of flocculation values of chloride and sulfate were 0.0001 - 0.0020 N and 0.0001 - 0.004 N respectively (Table 12). The values for $CaCl_2$ were in agreement with those found by Quirk and Schofield (1955) who showed that soils containing illite, kaolinite and vermiculite saturated with calcium were partially flocculated at 0.001M and completely flocculated at 0.002M $CaCl_2$. The range of $CaCO_3$ used in the flocculation series did not flocculate any of the soils. The solubility of $CaCO_3$ was also very low. Table 13 shows the flocculation values of each soil type and horizon in the order of decreasing concentration of cations. The results were in

Table 9. Flocculation values of Na-soils

Soil Type	NaCl		Na_2SO_4		$NaHCO_3$	
	N	pH Range	N	pH Range	N	pH Range
H_1	.075	6.30-6.55	.196	6.35-6.53	.250	6.40-8.55
H_2	.056	5.62-6.53	.058	5.80-6.80	.265	6.53-8.68
L_1	.028	5.88-6.35	.033	5.80-6.53	.145	6.35-8.72
L_2	.022	6.09-6.60	.026	6.22-6.75	.070	6.60-8.78
LK_1	.045	6.40-7.22	.064	6.65-7.20	.090	7.20-8.80
LK_2	.020	5.80-6.30	.024	5.90-6.40	.075	6.30-8.97
M_1	.036	5.30-5.89	.060	5.30-6.60	.300	5.89-9.40
M_2	.007	5.93-6.83	.015	5.30-6.27	.240	6.83-8.55
E_1	.050	6.70-7.10	.098	5.53-7.00	.275	7.10-8.50
E_2	.027	6.05-6.55	.044	6.30-6.55	.195	6.51-8.55
K_1	.017	5.60-6.27	.028	5.68-6.51	.265	6.27-8.95
K_2	.001	5.70-6.65	.005	6.10-6.65	.220	6.65-9.10

Table 10. Flocculation values for K-soils

Soil Type	KCl		K_2SO_4		$KHCO_3$	
	N	pH Range	N	pH Range	N	pH Range
H_1	.050	5.70-6.50	.070	6.06-6.70	.097	6.60-8.40
H_2	.033	5.70-6.20	.056	6.20-6.30	.095	6.20-8.30
L_1	.043	5.90-6.40	.054	6.20-7.00	.120	7.10-8.78
L_2	.033	5.73-6.54	.045	6.37-7.14	.035	6.47-8.50
L_3	.028	5.70-6.80	.037	6.13-7.05	.033	6.83-8.65
LK_1	.066	6.30-7.00	.075	6.50-7.25	.038	7.02-8.65
LK_2	.040	5.83-7.10	.050	6.28-7.10	.032	7.10-8.72
M_1	.031	5.50-6.30	.045	6.13-7.30	.049	6.20-8.66
M_2	.008	5.28-6.00	.008	5.72-7.10	.035	6.02-8.70
E_1	.044	5.60-6.60	.065	5.98-6.60	.107	6.60-8.40
E_2	.016	5.45-6.75	.025	5.90-6.45	.073	6.45-8.50
K_1	.008	5.70-6.70	.015	6.15-7.15	.037	6.60-8.55
K_2	.004	5.38-6.30	.004	5.85-7.20	.044	6.10-8.62

Table 11. Flocculation values of Mg-soils

Soil Type	$MgCl_2$		$MgSO_4$		$MgCO_3$	
	N	pH Range	N	pH Range	N	pH Range
H_1	.0017	5.50-5.90	.0019	5.70-5.90	*	6.00-8.70
H_2	.0014	5.45-6.10	.0015	5.70-6.05	*	6.10-7.30
L_1	.0017	5.18-6.45	.0021	5.89-6.32	*	6.71-9.32
L_2	.0014	5.35-5.90	.0019	5.59-5.91	*	5.96-8.90
L_3	.0016	5.50-5.90	.0017	5.61-6.00	*	5.95-8.87
LK_1	.0021	5.75-6.35	.0022	6.07-6.40	*	6.20-7.55
LK_2	.0015	5.68-6.00	.0015	5.80-6.25	*	6.05-7.72
M_1	.0014	5.51-5.81	.0015	5.60-6.00	*	5.80-8.50
M_2	.0004	5.18-5.45	.0005	5.28-5.70	*	6.10-7.65
E_1	.0017	5.40-5.80	.0022	5.49-6.00	*	5.80-8.74
E_2	.0004	5.40-5.80	.0007	5.50-5.82	*	6.54-8.80
K_1	.0003	5.60-5.82	.0003	5.70-7.00	*	6.10-8.40
K_2	.0001	5.60-5.93	.0001	5.78-6.21	*	6.01-8.12

*No flocculation

Table 11. Flocculation values of Mg-soils

Soil Type	$MgCl_2$		$MgSO_4$		$MgCO_3$	
	N	pH Range	N	pH Range	N	pH Range
H_1	.0017	5.50-5.90	.0019	5.70-5.90	*	6.00-8.70
H_2	.0014	5.45-6.10	.0015	5.70-6.05	*	6.10-7.30
L_1	.0017	5.18-6.45	.0021	5.89-6.32	*	6.71-9.32
L_2	.0014	5.35-5.90	.0019	5.59-5.91	*	5.96-8.90
L_3	.0016	5.50-5.90	.0017	5.61-6.00	*	5.95-8.87
LK_1	.0021	5.75-6.35	.0022	6.07-6.40	*	6.20-7.55
LK_2	.0015	5.68-6.00	.0015	5.80-6.25	*	6.05-7.72
M_1	.0014	5.51-5.81	.0015	5.60-6.00	*	5.80-8.50
M_2	.0004	5.18-5.45	.0005	5.28-5.70	*	6.10-7.65
E_1	.0017	5.40-5.80	.0022	5.49-6.00	*	5.80-8.74
E_2	.0004	5.40-5.80	.0007	5.50-5.82	*	6.54-8.80
K_1	.0003	5.60-5.82	.0003	5.70-7.00	*	6.10-8.40
K_2	.0001	5.60-5.93	.0001	5.78-6.21	*	6.01-8.12

*No flocculation

Table 12. Flocculation values of Ca-soils

Soil Type	$CaCl_2$		$CaSO_4$		$CaCO_3$	
	N	pH Range	N	pH Range	N	pH Range
H_1	.0020	6.05-6.18	.0040	6.25-6.40	*	6.40-7.50
H_2	.0020	6.10-6.29	.0030	6.30-6.60	*	6.64-8.20
L_1	.0024	5.82-6.00	.0030	6.00-6.51	*	6.40-7.20
L_2	.0010	5.60-6.30	.0024	5.88-6.40	*	6.20-7.50
L_3	.0018	5.92-6.35	.0023	6.11-6.62	*	6.20-7.20
LK_1	.0020	5.92-6.13	.0024	6.10-6.60	*	6.40-7.80
LK_2	.0020	6.01-6.20	.0022	6.16-6.58	*	6.53-7.40
M_1	.0012	5.18-5.30	.0022	5.32-5.50	*	5.02-6.73
M_2	.0005	5.32-5.95	.0005	5.70-6.45	*	6.00-7.60
E_1	.0010	5.20-5.60	.0015	5.41-6.20	*	5.60-7.40
E_2	.0002	5.60-5.78	.0003	5.91-6.52	*	5.95-7.37
K_1	.0012	5.42-5.70	.0020	5.76-6.43	*	6.26-7.45
K_2	.0001	5.40-6.00	.0001	5.95-6.35	*	6.50-7.30

*No flocculation

Table 13. Flocculation values in order of decreasing concentration of cations

Soil Type	Cl	$SO_4^=$	$HCO_3^-/CO_3^=$
Honouliuli A_p	Na>K>Mg≥Ca	Na>K>Ca>Mg	Na>K
Honouliuli B_2	Na>K>Ca>Mg	Na>K>Ca>Mg	Na>K
Lualualei A_1	K>Na>Ca>Mg	K>Na>Ca>Mg	Na>K
Lualualei A_{11}	K>Na>Mg=Ca	K>Na>Ca>Mg	Na>K
Lualualei A_c	K>Mg>Ca	K>Ca>Mg	
Lualualei A_i (Kokohead)	K>Na>Mg=Ca	K>Na>Mg=Ca	Na>K
Lualualei A_{ii} (Kokohead)	K>Na>Mg=Ca	K>Na>Ca>Mg	Na>K
Molokai A_p	Na>K>Mg>Ca	Na>K>Ca>Mg	Na>K
Molokai B_2	K>Na>Ca>Mg	Na>K>Mg=Ca	Na>K
Ewa A_p	Na>K>Mg>Ca	Na>K>Mg>Ca	Na>K
Ewa B_2	Na>K>Mg>Ca	Na>K>Mg>Ca	Na>K
Kawaihae A_1	Na>K>Mg>Ca	Na>K>Ca>Mg	Na>K
Kawaihae B_2	K>Na>Mg≥Ca	Na>K>Mg≥Ca	Na>K

general agreement with the Schulze-Hardy rule. Among monovalent cations, however, for some soils the flocculation values for Na salts were higher than for K, while for others, the flocculation values for K salts were higher than for Na. A similar relationship was observed between Mg and Ca salts, but the differences between salts of cations of similar valency were not as large as the differences between salts of cation of different valency. The above finding was also in agreement with the theory of the double-layer (Verwey and Overbeek, 1948, van Olphen, 1963, among others), which predicted that a lower concentration of electrolyte of divalent cation than monovalent cation was necessary for the flocculation of a suspension.

2. Effects of Anions

By comparison of flocculation values (Tables 9-12), for the effects of anions, it can be seen that for all soils and cations, the flocculation values decreased in the order of $HCO_3^-/CO_3^=$ > $SO_4^=$ > Cl^-. Similar results were also found by Nakayama (1966) and El-Swaify (1973), using dispersion and hydraulic conductivity respectively as the indices of stability of soil. While the pH ranges for chloride and sulfate systems were not markedly different, the pH ranges for bicarbonate and carbonate systems were much higher than those of chloride and sulfate systems (refer to Tables 9-12).

These differences in pH readings very likely caused most of the variation in stability of the clay suspensions as measured by the flocculation values. Higher pH favors the stability of the suspensions due to increased negative charges on the clays and hydroxides which increased interparticle repulsive energy. The difference between

chloride and sulfate ions in spite of similar pH values, was due to the differences in valencies of the two anions. Sulfate ions, having two negative charges, would attract more of the cations in solution than chloride, lowering the concentration or activity of the cations near the clay surfaces in the diffuse double layer. This reduction in cation concentration and activity would decompress the double layer and thus the stability of the colloidal would be increased.

Another reason for the difference in flocculation values between suspensions containing sulfate and chloride ions was that when those ions were adsorbed on the positively charged edges of kaolinite, oxides and hydrous oxides or amorphous colloids, sulfate, having a valency twice as much as chloride was more effective than chloride in neutralizing these positive charges; thus a higher concentration of the chloride ions was necessary to reduce the electric potential to that which flocculated the soil.

3. Effects of Soil Horizons

Referring again to Tables 9-12, it can be seen that the flocculation values of surface soils were consistently higher than those of subsurface soils. Appendix A shows that the organic matter content for surface soils was higher than for subsurface soils. Organic matter and its byproducts such as $COOH^-$ and OH^- have negative charges, which, due to increases in the electric potential of the system, increased the stability of the suspension of the surface soil relative to the subsurface sample.

As mentioned in the section on dispersion of homoionic soils, the base saturations of the surface soils were higher than if not

equal to those of the subsurface soils. The exchange sites not occupied by exchangeable bases must have been filled with Al^{3+} and H^{+} ions. Some of these Al^{3+} ions, having a higher energy of adsorption than monovalent or divalent ions, may not have been replaced by the cations used in the leaching during the preparation of homoionic soils. The presence of Al^{3+} on the exchangeable sites of the subsurface horizon more than on the surface horizon, may have reduced the stability of the subsurface soil suspensions such that less concentration of salt was required to reach the flocculation value.

The CEC of the surface soil was also higher than that of the subsurface soil. This means that there was a greater negative charge on the surface soil than on the subsurface soil, which increased the activity of the clays and thus the repulsive energy between the negatively charged clay particles. This required a greater concentration of electrolyte to flocculate the soil suspensions.

4. Effects of Soil Types

Since the results were found to be different for the surface and subsurface soils, the soil types will be compared within the same horizon, though the depths sampled were not exactly the same in all soils.

For surface soils, the flocculation values were found to be in the following order of soil types.

NaCl: $H_1 > E_1 > LK_1 > M_1 > L_1 > K_1$

Na_2SO_4: $H_1 > E_1 > LK_1 > M_1 > L_1 > K_1$

$NaHCO_3$: $M_1 > E_1 > K_1 > H_1 > L_1 > LK_1$

KCl: $LK_1 > H_1 > E_1 = L_1 > M_1 > K_1$

K_2SO_4: $LK_1 > H_1 > E_1 > L_1 > M_1 > K_1$

$KHCO_3$: $L_1 > E_1 > H_1 > K_1 > M_1 > LK_1$

$MgCl_2$: $LK_1 \geq H_1 = L_1 = E_1 \geq M_1 > K_1$

$MgSO_4$: $E_1 = LK_1 \geq L_1 \geq H_1 \geq M_1 > K_1$

$CaCl_2$: $L_1 \geq H_1 = LK_1 \geq M_1 = K_1 \geq E_1$

$CaSO_4$: $H_1 \geq L_1 \geq LK_1 \geq M_1 \geq K_1 \geq E_1$

For subsurface soils, the following order of decreasing flocculation values for soils were found:

NaCl: $H_2 > E_2 > L_2 > LK_2 > M_2 > K_2$

Na_2SO_4: $H_2 > E_2 > L_2 > LK_2 > M_2 > K_2$

$NaHCO_3$: $H_2 > M_2 > K_2 > E_2 > LK_2 > L_2$

KCl: $LK_2 \geq L_2 \geq H_2 > E_2 > M_2 > K_2$

K_2SO_4: $H_2 > LK_2 \geq L_2 > E_2 > M_2 > K_2$

$KHCO_3$: $H_2 > E_2 > L_2 > K_2 > M_2 > LK_2$

$MgCl_2$: $LK_2 \geq H_2 \geq L_2 > E_2 \geq M_2 > K_2$

$MgSO_4$: $L_2 \geq H_2 \geq LK_2 > E_2 \geq M_2 > K_2$

$CaCl_2$: $H_2 \geq LK_2 \geq L_2 \geq M_2 > E_2 \geq K_2$

$CaSO_4$: $H_2 \geq L_2 \geq LK_2 \geq M_2 \geq E_2 \geq K_2$

There were no flocculation values for any soil studied in $MgCO_3$ and $CaCO_3$ solutions (flocculation was not produced) except for

subsurface Kawaihae soil, which required only minimum electrolyte concentration to be flocculated.

The results showed that, within the same horizon and monovalent cation, the order of decreasing flocculation values of soils in sulfate solutions were the same as those of chloride solution. The order was however changed in bicarbonate solution, and from cation to cation. This implies that the relative stability of the soils changed from cation to cation and from chloride and sulfate on one hand to bicarbonate and carbonate on the other. This was as expected due to different influences of the cations and anions due to valency or pH as was discussed before. In monovalent cation solution for both soil horizons, the differences in flocculation values between soil type, in the order shown above, seemed significant.

It was found that the flocculation values of KCl and K_2SO_4 for surface soils were higher for the Lualualei from Kokohead, Lualualei and Honouliuli as a group than Ewa, Molokai, and Kawaihae; and the flocculation values of these latter three soils were also different significantly in decreasing order.

For subsurface soils in Mg solutions, the flocculation values of Lualualei from Kokohead, Lualualei, and Honouliuli soils on one hand were considerably higher than those of Ewa, Molokai, and Kawaihae on the other. In Ca solution, however, for both horizons, there were no differences between flocculation values of different soil types.

The differences in soil mineralogical composition and other properties must have affected these differences. Studying the

properties of the soils (Appendices A and B, Hawaiian Soil Data Bank, 1965; and Kanehiro, et al., 1956) it can be seen that soils having clay minerals of expanding 2:1 type or with higher organic matter content or both, had higher flocculation values compared to other soils. This was expected because, as mentioned earlier, 2:1 clays had higher CEC than the kaolinitic soils, and thus had a higher negative charge or electrokinetic potential. The presence of organic matter and its byproducts which were mostly negatively charged, would require a higher amount of electrolyte to bring the potential to the value that flocculated the soil suspensions. In carbonate/bicarbonate solutions, the soils with pH dependent characteristics such as those containing the oxides or kaolinites had higher flocculation values than the soils with permanent charge type (the Vertisols). This was because the high pH values of the carbonate system increased negative charge of the former group of soils, and required a higher concentration of electrolyte in order to be flocculated. This was demonstrated as in the case of surface soils in $NaHCO_3$ solution in which the Molokai, Ewa, and Kawaihae suspensions seemed to be more stable than the Honouliuli, Lualualei, and Lualualei from Kokohead suspensions.

For the subsurface soil in $NaHCO_3$, the Honouliuli suspension seemed to be more stable than the Molokai, Kawaihae, and Ewa, while the Lualualei from Kokohead and Lualualei were less stable, having a lower flocculation value. In $KHCO_3$, while Honouliuli suspension was still the most stable and Lualualei from Kokohead the least, the Lualualei suspension became more stable, having a flocculation value somewhere between those of Ewa and Kawaihae. This latter finding is difficult to explain.

B. Exchangeable Sodium Percentage (ESP) and Exchangeable Potassium Percentage (EPP) for Dispersion/Flocculation

All suspensions under different ESP or EPP in 0.1 N electrolyte concentration were flocculated. Quirk and Schofield (1955) defined the "threshold concentration" for an electrolyte as the concentration below which 10-15% decreases in permeability were noted. For soils containing kaolinite, illite, vermiculite, and saturated with respective cations of salt solutions, the threshold concentration for NaCl, KCl, $MgCl_2$, and $CaCl_2$ were .25 M, .067 M, .001 M, and 3×10^{-4} M, respectively. The flocculation of all soil suspensions at 0.1 N fits into the finding of Quirk and Schofield, though the value 0.25 M for NaCl of Quirk and Schofield was higher, it is to be remembered that they were working with homoionic systems as compared to two ionic systems in this study.

Table 13 shows the percentage of < 2 μ clay still remaining in suspension at different ESP or EPP in 0.01 N electrolyte concentration, obtained from appropriate curves similar to the ones shown in Figures 6 and 7. Table 14 shows similar results for the Molokai, Ewa, and Kawaihae soils and for all soils in 0.005 N electrolyte concentration.

1. Exchangeable Sodium Percentage (ESP) and Exchangeable Potassium Percentage (EPP) in 0.01 N Electrolyte Concentration

a. Effect of Complementary Divalent Cation

Referring to Tables 14 and 15, the exchangeable sodium percentages and exchangeable potassium percentages needed to produce flocculation are those values at which the percentage of clay remaining in suspension is 0. Taking an arbitrary value of 25% for suspended

Table 14. Exchangeable Sodium Percentage (ESP) and Exchangeable Potassium Percentage (EPP) for flocculation/dispersion of soil suspensions in 0.01 N electrolyte concentration

Soil Type	Na-Ca system		Na-Mg system		K-Ca system		K-Mg system	
	ESP	% clay remaining in suspension	ESP	% clay remaining in suspension	EPP	% clay remaining in suspension	EPP	% clay remaining in suspension
H_1	5	0	5	0	15	0	15	0
	7	25	10	20	25	15	25	13
	10	50	12*	25	33*	25	35*	23
	15	87	15	43	40	50	45	50
H_2	10	0	10	0	15	0	25	0
	15	20	15	18	25	13	50*	25
	17*	42	20*	25	33*	25	60	50
	30	75	25	33	40	50	-	-
L_1	15	0	15	0	5	0	10	0
	25	20	10	25	10	20	15	63
	33*	40	18*	50	15	23	25	75
	40	50	25	75	25*	45	-	-
L_2	10	0	15	0	10	0	25	0
	15	20	25	18	15	33	50	23
	20*	37	50*	33	20	43	57*	38
	25	55	60	50	25	50	60	50
LK_1	5	0	10	0	15	0	10	0
	10	20	15	22	25	20	15	33
	15	30	30*	38	33*	38	17*	40
	25*	50	85	50	38	50	20	50
LK_2	10	0	15	0	15	0	25	0
	15	18	20*	25	25	18	50	15
	20	22	25	38	34*	30	56*	30
	45*	25	37	50	43	50	60	50

*ESP or EPP at inflection point of curves relating suspended clay % and ESP or EPP.

Table 15. Exchangeable Sodium Percentage (ESP) for flocculation/dispersion of soils at 0.005 N and 0.01 N electrolyte concentration (Na-Ca systems)

Soil Type	0.005 N		0.01 N	
	ESP	% clay remaining in suspension	ESP	% clay remaining in suspension
H_1	0	0	*	*
	5	68		
	10	100		
H_2	0	0	*	*
	5	25		
	10	88		
L_1	0	0	*	*
	5	75		
	10	88		
L_2	0	0	*	*
	5	38		
	10	88		
LK_1	0	0	*	*
	5	30		
	10	100		
LK_2	0	0	*	*
	5	25		
	10	68		
M_1	0	0	5	0
	5	25	10	25
	10	35	15	35
M_2	0	0	0	0
	75	0	75	0
E_1	0	0	5	0
	5	30	10	15
	10	68	15	25
E_2	5	0	15	0
	10	20	25	18
	15	38	30	25
K_1	5	0	10	0
	10	15	15	20
	20	38	20	25
K_2	0	0	0	0
	75	0	75	0

*Values are as shown in Table 14.

clay as an indication that the soil become dispersed in the field under a certain condition, it can be seen that it required a higher percentage of exchangeable Na or K in Na-Mg or K-Mg system than in Na-Ca or K-Ca system to disperse the suspension. Though the ESP or EPP for flocculation in the Mg system was higher than in Ca system in most soils, the dispersion versus ESP (or EPP) curves (similar to those in Figures 6 and 7) of most soils showed that, the part of the curve between ESP or EPP for flocculation and higher values was found to rise more sharply in Mg-system than in Ca-system. This indicated that after ESP or EPP for flocculation has been reached, additional units of ESP or EPP would cause more dispersion in Mg-soils than in Ca-soils. All the above results were in general agreement with those of other investigators such as Bakker, et al. (1973), Emerson (1967), and others.

b. Relative Effect of Na and K

For all soils with the same divalent cation as the complementary ion, the K-system seemed to be less dispersed than the Na-system, as indicated by the higher percentage of exchangeable K than Na required to disperse the suspension by about the same degree. This may be attributed to the differences in degree of hydration of the two ions, Na having a thicker "hydration shell" than K.

c. Effect of Soil Horizons

Comparing soil horizons, it was shown that the ESP or EPP necessary to produce about 25% dispersion was higher for the subsurface sample than the surface sample, agreeing with what was found in the flocculation series test, and indicating that the surface horizon was more sensitive to dispersion than the subsurface due to the presence of organic matter and its products and lower percentage of exchangeable

acidity.

d. Effects of Soil Types

If a value of ESP in a Na-Ca system had to be chosen to indicate a 25% dispersion of the soil suspensions, then values of (in increasing ESP or colloidal stability) 7%, 10%, 10%, 15%, 20%, and 25% are found for the surface soils of the Honouliuli, Molokai, Lualualei from Kokohead, Ewa, Kawaihae, and Lualualei, respectively. The values for subsurface horizons of the Lualualei, Honouliuli, Lualualei from Kokohead, and Ewa, respectively, are 15%, 15%, 20%, and 30%. Kawaihae and Molokai subsurface horizons were flocculated even at ESP of 75%. The ESP (in the Na-Ca system) at which the suspensions were totally flocculated were 5% each for surface horizon of the Molokai, Ewa, Honouliuli, and Lualualei from Kokohead; and 10% and 15% respectively for Kawaihae and Lualualei. For the subsurface soils, the ESP's for flocculation were 10% each for the Honouliuli, Lualualei, and Lualualei from Kokohead; and 15% for Ewa.

2. Exchangeable Sodium Percentage for Dispersion/ Flocculation in 0.005 N Electrolyte Concentrations (Na-Ca System Only)

The results for this experiment, as shown in Table 15, indicated that the suspensions were more stable in 0.005 N than in 0.01 N electrolyte concentration. Most of the soil suspensions were only flocculated when there was no exchangeable sodium on the clay exchange surfaces. The subsurface suspensions of Molokai and Kawaihae were, however, unstable, being flocculated even at ESP of 75%. The subsurface sample of Ewa became flocculated at ESP of 5%.

In order to compare the relative stability of the suspensions in 0.005 N electrolyte concentration due to soil type, the ESP to produce 25% dispersion will again be used. For the surface horizons the ESP values are < 5% each for Honouliuli, Lualualei, and Lualualei from Kokohead; 5% each for Molokai and Ewa; and 15% for Kawaihae. For the subsurface horizons, the ESP values are < 5% for Lualualei, 5% each for Honouliuli and Lualualei from Kokohead, and 15% for Ewa. The Molokai and Kawaihae subsurface soils were flocculated even at 75% ESP.

Emerson (1967) noted that illite or montmorillonitic soils which dispersed spontaneously and completely in water had exchangeable percentages of between 17-55%, while those that showed perceptible dispersion had a minimum ESP of 7%. Soils which only dispersed in water after being remoulded at field capacity, consist mostly of kaolin and hematite, with little montmorillonite in some cases. The pH range of these aggregates (subsoil) was 7.4-6.6 and the ESP varied from 3% to 14%. Emerson, et al. (1973) observed that Shepparton fine sandy loam soil aggregates with ESP of 6% dispersed spontaneously in water to between 26-31%.

SUMMARY AND CONCLUSION

1. Surface soil aggregates of Molokai silty clay, Lualualei clay, Lualualei clay from Kokohead, Honouliuli clay, Ewa clay, and Kawaihae very fine sandy loam soils were classified according to Emerson's classification scheme (1967), with some modifications. All the air-dry soil aggregates slaked, and samples of the Lualualei soil from Kokohead dispersed partially in addition to slaking. The Lualualei from Kokohead was thus classified into class 2 since it showed some dispersion. All other soils, except the Molokai, were classified under class 3 since they dispersed in distilled water after remoulding at a moisture content approximately that of field capacity. The Molokai soil which dispersed in 1:5 soil-water suspensions was classified into class 5. Different degrees of dispersion and slaking were noted for different soils, which could be used to classify the soils into subclasses.

2. When surface soil aggregates, wetted at 100 cm, 50 cm, 30 cm, and 15 cm suction were immersed in distilled water, it was found that regardless of prewetting treatments, the Molokai, Ewa and Honouliuli soil aggregates remained intact (did not slake). Other soil aggregates showed some degree of slaking depending on the wetting or suction, and the Lualualei from Kokohead samples always showed some dispersion in addition to slaking. At 30 cm suction, however, it was noted that the Lualualei aggregates did not slake, probably due to the absence of incipient failure at that water content.

3. When homoionic soils were remoulded at different water contents, it was found that generally the monovalent-saturated samples were more

dispersed than the divalent-saturated samples. While the dispersion of monovalent-saturated samples decreased with increasing remoulding water content, the divalent-saturated samples increased to a maximum, and then decreased again. The minimum water content to induce dispersion was found to be lower for monovalent saturated samples than for divalent-saturated samples. The above findings were in general agreement with the predictions of electric-double layer theory and with the results of other workers. It was also found that the dispersion for surface soils was greater than for the subsurface soils, but the differences varied according to soil type. This was attributed to more organic matter content and less exchangeable Al^{3+} in the surface than in the subsurface soil. In comparing soil types, it was observed that the Vertisols (Honouliuli, Lualualei, and Lualualei from Kokohead) consisting of expanding 1:1 and 2:1 clays, were more dispersed than Molokai, Ewa and Kawaihae soils which contained in different proportions kaolinite, amorphous materials, gibbsite, and hematite. These differences were also attributed to a higher cation exchange capacity in the former group than the latter, and although Kawaihae soil had a similar CEC to the Vertisols, it also had lower base saturation.

4. When the natural aggregates of surface soils at 50 cm suction were immersed in 0.001M sodium pyrophosphate, it was found that the soils dispersed in the following decreasing order: Lualualei from Kokohead > Honouliuli > Lualualei > Ewa > Molokai > Kawaihae, with the Kawaihae not dispersing at all. When aggregates were first immersed in 0.1M sodium pyrophosphate solution overnight, followed by decantation and subsequent slow addition of 0.001M sodium phosphate solution, the

dispersion of the soils after 24 hours was as follows: Honouliuli > Lualualei from Kokohead > Lualualei > Ewa > Molokai > Kawaihae. The Kawaihae soil again did not disperse. There was a marked increase in dispersion of Honouliuli, Lualualei, Lualualei from Kokohead, and to some extent Ewa soil. This was attributed to increased adsorption of exchangeable sodium and negative pyrophosphate ions thus increasing the electric potential and the repulsive forces of the particles.

5. In the Flocculation Series Tests involving anions of sodium, results showed that flocculation values decreased in the following order: $HCO_3^-/CO_3^=$ > $SO_4^=$ > Cl^-. The pH's of the $HCO_3^-/CO_3^=$ systems were found to be higher than those of $SO_4^=$ and Cl^- systems, which increased the negative charges of the clays and hydroxides and thus increased the interparticle repulsive energy. Valency of the anions also affected the difference in flocculation values.

With regards to effects of cations, results for flocculation values followed the Schulze-Hardy rule. For all soils, the flocculation values of Cl^-, $SO_4^=$ and HCO_3^- of sodium fell in the range of 0.001 - 0.075 N, 0.005 - 0.196 N, and 0.070 - 0.300 N respectively. The flocculation values were 0.004 - 0.066 N, 0.004 - 0.075 N and 0.032 - 0.120 N for Cl^-, $SO_4^=$ and HCO_3^- of potassium. For $MgCl_2$ and $MgSO_4$, the values were 0.0001 - 0.0020 N for both salts. There was no flocculation produced at the range of concentration of $MgCO_3$ used in the experiment. For Ca-salts, the ranges of flocculation values of Cl^- and $SO_4^=$ were 0.0001 - 0.0020 N and 0.0001 - 0.0040 N, respectively. The solubility of $CaCO_3$ being low, no flocculation could be induced by this salt. The flocculation values of surface soils were higher than for the subsurface soils, due to higher organic matter content, lower exchangeable acidity and higher CEC of the

surface horizons.

Soils having expanding type clays, permanent charge characteristics, high organic matter content, or higher clay content generally had higher flocculation values in chloride and sulfate solutions than other soils. In bicarbonate/carbonate solutions, however, soils with pH-dependent characteristics had higher flocculation values than those of permanent charge type. Most probably this is the result of increased negative charges at the high pH values prevailing in the bicarbonate/carbonate systems; thus higher concentrations of electrolyte were required to flocculate the suspended soil particles. The flocculation values due to cations were as follows: Na > K > Mg > Ca.

6. Higher exchangeable potassium percentage (EPP) than exchangeable sodium percentage (ESP) was required for dispersion of a given soil to about the same degree. In comparing the effects of Mg and Ca as complementary ions to Na or K, it was found that Mg caused more dispersion than Ca. The ESP values required to cause 25% dispersion in 0.01 N electrolyte concentration ranged from 7-25% for the surface soils, and from 15-30% for subsurface soils with the exception of subsurface samples of Kawaihae and Molokai soils which remained flocculated even at an ESP of 75%. The soil suspensions were more stable in 0.005 N electrolyte concentration than in 0.01 N and the ESP values for 25% dispersion in the first were from 5-15% for surface soils, and 5-15% for subsurface soils of Honouliuli, Lualualei, Lualualei from Kokohead, and Ewa. The subsurface horizons of Molokai and Kawaihae again remained flocculated even at 75% ESP.

Appendix A. Approximate abundance of soil constituents

Soil	Mineral Constituents[a]													Organic matter[b]
	A	F	Gi	Gp	He	Ha	I	K	Magh	Magn	O	Q	S	%
M_1	3	-	3	4	3	5	-	3	3	5	-	4	-	0.83
M_2	3	-	3	4	3	5	-	3	3	5	-	4	-	0.53
E_1	2	-	4	4	3	-	-	2	-	5	-	5	-	2.55
E_2	2	-	4	4	3	-	-	2	-	5	-	5	-	0.76
H_1	3	-	4	4	4	-	-	2	-	-	4	-	-	1.25
H_2	3	5	5	4	4	-	4	2	-	-	4	-	-	0.36
L_1	3	5	3	3	4	-	5	3	-	5	4	4	-	1.14
L_2	3	4	3	3	4	-	5	3	-	5	4	4	-	0.72
L_3	3	4	3	3	4	-	5	3	-	5	4	4	-	0.36
LK_1	2	3	-	4	4	-	-	5*	4	-	-	4	4	1.61
LK_2	2	3	-	4	4	-	-	5*	4	-	-	4	4	0.91
K_1	2	-	5	-	4	-	-	4	4	4	4	-	-	0.83
K_2	2	-	5	-	4	-	-	4	4	4	4	-	-	0.40

[a]Reported information is based on x-ray diffraction of the (silt + clay) fractions. For Lualualei samples, only the clay fractions were analyzed.

[b]Data obtained from the unpublished Soil Data Bank, Department of Agronomy and Soil Science, University of Hawaii.

Legend

A = Amorphous (including some organic material)
F = Feldspar
Gi = Gibbsite
Go = Goethite
He = Hematite
Ha = Halloysite
I = Inter-stratified
K = Kaolinite
Magh = Maghemite
Magn = Magnetite
O = Olivine
Q = Quartz
S = Smectite
1 = 40% or more
2 = 25-40%
3 = 10-25%
4 = 1-10%
5 = detected

*Unidentified member of the kaolin group.

Appendix B. Values of q_o for Ca-, Mg-, Na-, and K-saturated soils in me/100 gm

Soil	Horizon	Sym.	Ca	Mg	Na	K
Molokai	A_p	M_1	15.00	15.36	18.06	19.06
	B_2	M_2	10.34	10.17	11.41	9.57
Ewa	A_p	E_1	14.69	18.05	15.86	19.20
	B_2	E_2	13.83	14.28	14.43	14.62
Honouliuli	A_p	H_1	26.23	30.81	27.00	34.80
	B_2	H_2	27.59	28.45	26.43	36.65
Lualualei	A_1	L_1	41.97	39.11	39.69	52.33
	A_{11}	L_2	35.02	41.98	35.76	53.75
	A_c	L_3	33.16	35.81	34.13	52.96
Lualualei from Kokohead	A_1	LK_1	57.19	68.79	51.92	106.61
	A_{11}	LK_2	57.69	53.44	48.60	95.91
Kawaihae	A_1	K_1	15.52	19.23	24.38	34.47
	B_2	K_2	12.96	12.77	19.46	26.54

Appendix C. Surface areas of Ca-, Mg-, Na-, and K-saturated soils in m^2/gm

Soil	Ca	Mg	Na	K
M_1	121	104	82	80
M_2	99	96	71	62
E_1	111	105	91	68
E_2	88	97	86	51
H_1	200	173	159	88
H_2	185	172	143	89
L_1	253	239	204	153
L_2	246	235	201	150
L_3	244	241	199	148
LK_1	370	308	274	117
LK_2	363	338	297	200
K_1	167	152	143	111
K_2	171	157	143	129

Appendix D. pH of Ca-, Mg-, Na-, and K-saturated surface and subsurface soils

Soil	Ca	Mg	Na	K
M_1	6.476	6.595	7.577	7.549
M_2	6.847	6.703	7.461	7.161
E_1	6.909	6.663	7.852	7.855
E_2	6.928	6.918	7.722	7.695
H_1	7.151	6.998	8.284	8.222
H_2	7.211	7.118	8.296	8.057
L_1	7.038	7.478	8.476	8.463
L_2	7.276	7.199	8.337	8.033
L_3	7.330	7.151	8.337	8.062
LK_1	7.106	8.180	9.080	8.480
LK_2	7.355	7.480	8.620	8.750
K_1	7.802	7.060	7.070	7.030
K_2	6.457	6.390	7.160	6.800

Appendix E. Dispersion index at different moisture contents of Na-soils

Soil Type	1:5 Soil-water ratio		2:5 Soil-water ratio		3:5 Soil-water ratio		4:5 Soil-water ratio	
	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)
H_1	31.45	80.66	52.97	77.01	76.38	75.56	96.08	79.35
H_2	29.85	100.00	49.62	94.78	74.28	71.21	92.50	76.22
L_1	19.89	87.89	29.70	67.41	51.16	73.23	77.65	62.09
L_2	26.67	89.05	50.80	84.80	71.97	96.70	89.95	98.81
LK_1	32.81	65.43	54.66	66.08	72.24	65.67	105.32	52.72
LK_2	41.93	78.70	62.02	72.42	90.90	82.86	108.48	76.28
M_1	28.68	71.08	48.29	48.40	68.47	28.63	89.84	14.75
M_2	19.60	9.63	47.41	27.49	63.95	20.83	84.82	13.75
E_1	27.68	59.87	46.98	27.71	67.87	24.61	90.91	18.86
E_2	28.54	64.37	47.64	30.42	65.08	28.61	91.92	25.33
K_1	27.84	45.48	52.60	35.90	79.41	27.51	91.89	22.22
K_2	35.33	45.68	59.28	22.85	77.50	16.66	101.51	16.33

Appendix F. Dispersion index at different moisture contents of K-soils

Soil Type	1:5 Soil-water ratio		2:5 Soil-water ratio		3:5 Soil-water ratio		4:5 Soil-water ratio	
	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)
H_1	30.69	51.39	51.09	15.74	70.53	14.95	92.45	19.96
H_2	30.17	70.81	51.78	27.76	73.52	27.60	95.26	19.84
L_1	30.02	61.50	52.94	22.51	74.70	8.72	91.28	7.41
L_2	30.33	71.04	51.69	24.68	78.84	11.95	92.76	11.06
L_3	32.45	51.78	54.16	20.22	74.05	12.81	93.76	10.21
LK_1	28.91	57.93	49.53	27.36	74.64	22.51	94.46	5.71
LK_2	34.89	52.42	56.61	27.51	86.08	13.19	104.16	7.18
M_1	26.66	40.21	49.21	44.29	71.85	25.23	89.20	15.28
M_2	29.17	36.57	48.67	51.76	71.75	30.81	87.70	24.03
E_1	27.64	48.47	49.68	28.11	70.38	18.50	88.74	15.20
E_2	27.81	73.05	47.43	31.48	68.44	26.31	90.94	27.09
K_1	34.96	66.79	52.76	11.72	55.16	6.06	97.53	5.31
K_2	32.68	0	53.30	6.14	81.81	3.98	98.99	6.30

Appendix G. Dispersion index at different moisture contents of Ca-soils

Soil Type	1:5 Soil-water ratio		2:5 Soil-water ratio		3:5 Soil-water ratio		4:5 Soil-water ratio	
	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)
H_1	28.35	0	49.27	8.12	69.91	9.25	88.46	1.44
H_2	28.46	0	47.46	2.68	74.13	13.99	89.07	6.27
L_1	30.95	0	51.88	10.85	72.07	7.55	92.75	3.65
L_2	31.52	0	50.61	9.92	71.25	9.62	90.10	6.71
L_3	35.08	0	58.72	4.94	80.86	14.01	108.96	9.06
LK_1	137.38	0	56.34	0	77.82	7.17	100.83	8.53
LK_2	38.49	0	59.17	3.18	87.41	5.72	97.93	7.65
M_1	26.24	0	46.18	9.16	87.29	5.26	100.25	8.61
M_2	27.75	0	48.04	0	68.39	3.65	85.95	5.43
E_1	26.85	0	63.77	11.56	82.79	5.23	100.85	10.35
E_2	44.14	0	63.87	10.21	82.35	6.37	100.40	10.26
K_1	31.16	3.55	64.54	8.22	79.62	8.10	107.29	8.90
K_2	32.25	0	55.72	7.22	80.70	4.05	94.83	3.71

Appendix H. Dispersion index at different moisture contents of Mg-soils

Soil Type	1:5 Soil-water ratio		2:5 Soil-water ratio		3:5 Soil-water ratio		4:5 Soil-water ratio	
	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)	Moisture content (%)	D.I. (%)
H_1	33.88	38.82	54.21	18.79	80.60	14.94	96.56	17.57
H_2	31.44	0	52.99	14.11	76.18	15.50	101.41	17.14
L_1	32.53	8.25	56.00	18.60	75.48	12.41	98.39	10.49
L_2	34.12	1.45	55.93	20.71	77.61	20.29	97.04	18.33
L_3	34.27	1.55	56.78	12.99	80.60	18.32	101.29	20.40
LK_1	35.64	0	60.47	6.99	73.18	9.82	99.22	13.72
LK_2	38.44	0	58.55	21.60	78.68	22.52	104.68	17.79
M_1	25.86	0	47.18	3.19	67.71	7.79	86.29	11.65
M_2	26.48	0	45.11	0	69.19	3.10	87.36	6.66
E_1	27.75	0	49.20	4.82	75.34	13.81	91.46	21.26
E_2	29.72	0	46.22	0	73.89	5.78	88.63	9.26
K_1	35.09	1.41	52.83	5.75	78.36	7.29	105.88	5.25
K_2	37.95	0	55.98	3.33	87.85	3.67	108.62	3.12

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